[INTERN]ATIONAL POPLAR RIVER [W]ATER QUALITY STUDY

Appendix B: Ground Water Quantity and Quality

1979

INTERNATIONAL POPLAR RIVER WATER QUALITY STUDY

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Prepared by the Ground Water Quantity and
Quality Committee of the International
Poplar River Water Quality Board,
International Joint Commission

1979

March 1979

Mr. E. H. Cornford
Co-Secretary, Canada
International Poplar River Water Quality Board

Dear Mr. Cornford:

We are pleased to enclose the original and a copy of the report "Effects of the Saskatchewan Power Corporation Power Plant on Quantity and Quality of Ground Water in the Poplar River Basin Saskatchewan - Montana". This report was prepared by the Ground Water Quantity and Quality Committee of the International Poplar River Water Quality Board. Board members and other committee co-chairmen have had a copy of this report since October 1978. Several changes have, however, been made in the original text issued in October.

The report includes our study design, conclusions, recommendations, and a synopsis. Annexes to this report are available from Mr. D. H. Lennox Canadian Co-Chairman.

D. Lennox, Canadian Co-Chairman
Ground Water Quantity & Quality Comm.

R. Averett, U.S. Co-Chairman
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G. Grisak, Canadian Member

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O. Taylor, U.S. Member

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* Assisted in the early deliberations of the Committee. Other work commitments necessitated their resignation and they were replaced by G. Grisak and S. Stan.

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Simplified Glossary of Terms

Anisotropy.--A condition in which properties differ according to the direction of measurement.

Aquifer.--A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Aquifer test.--A field procedure used to determine the transmissive and storage characteristics of an aquifer. Commonly consists of measurement of the hydraulic or chemical response of the aquifer to a pumped well, injection well, changes in stream stage, or tracers.

Artesian aquifer.--See confined aquifer.

Bank storage.--Temporary storage of water in an aquifer adjacent to a stream, caused by a rise in stream stage that induces movement of stream water into the aquifer. Water in bank storage normally returns to the stream as stream stage declines.

Base flow.--Natural discharge from the ground-water reservoir to a stream. The discharge maintains streamflow in the absence of surface runoff.

Bedding planes.--The zones of separation between horizontal layers of sedimentary deposits.

Cone of depression.--See drawdown.

Confined Aquifer.--An aquifer containing ground water that is enclosed under pressure between relatively impermeable or significantly less permeable material, and from which water will rise above the top of the aquifer if the aquifer is penetrated by a well.

Conservative chemical consituent.--An element or compound that is not reduced in concentration by chemical activity during transit.

Contaminant.--A chemical constituent having a high enough concentration to degrade the quality of water.

Digital model.--See mathematical model.

Dissolved-solids concentration.--The dissolved minerals in water expressed as the weight of minerals per unit volume of water, without regard to the type of mineral.

Drawdown.--Lowering of the water table or potentiometric (piezometric) surface caused by the extraction of ground water by pumping, by artesian flow from a bore hole, or by a spring emerging from an aquifer.

Evapotranspiration.--Loss of water by evaporation from wet surfaces and by transpiration through plants.

Exchange capacity.--The quantitative ability of a sediment to sorb cations or anions from solutions with the release of the previously sorbed ions.

Fracture.--A planar opening in rock or sediment, through which water may move.

Flow net.--A system of streamlines and orthogonal equipotential lines. The drop of potential between adjacent equipotential lines is constant and the spacing between neighboring streamlines is such that the flow rate is the same between each pair.

Gain-and-loss study.--A series of surface-water flow measurements in a reach of a stream to determine increases or decreases in streamflow attributable to interchanges between the stream and associated aquifer.

Gaining stream.--A stream or reach of a stream in which flow is being increased by inflow of ground water.

Ground-water discharge.--Loss of water from a ground-water reservoir.

Ground-water divide.--The line or surface of separation between adjacent independent ground-water flow systems.

Ground-water level.--Used in the sense of potentiometric surface.

Ground-water mound.--Mound or ridge-shaped feature in a ground water table resulting from influent seepage.

Ground-water recharge.--Addition of water to a ground-water reservoir.

Hydraulic conductivity.--Rate at which water may be transmitted through a unit area of an aquifer under standardized conditions.

Hydraulic gradient.--Change in hydraulic head per unit length of flow path.

Hydraulic head.--The position of a ground-water level in relation to some datum.

Hydrologic boundary.--Lateral discontinuity in geologic material, marking the transition from the permeable material of an aquifer to a material of significantly different geohydrologic properties.

Leakage.--In ground water, the flow of water from or into an aquifer through an underlying or overlying semipervious layer.

Losing stream.--A stream or reach of a stream that is losing water to the ground-water reservoir.

Mathematical model.--Mathematical technique used to simulate the response of a system to natural or man-induced conditions.

Matrix.--See rock matrix.

Piezometric surface.--See potentiometric surface.

Potentiometric surface.--An imaginary surface connecting points to which water would rise in tightly cased wells receiving water from given points in an aquifer. A map of the potentiometric surface is useful to indicate direction of ground-water movement.

Return flow.--That part of irrigation water that is not consumed by evapotranspiration and that returns to its source of another surface water body. The term also is applied to water that is discharged from industrial plants. Also called return water.

Rock matrix.--Principal rock fabric and cementing material.

Simulation.--Technique used to imitate and study the behavior of a system under existing or proposed conditions. Commonly used to predict the response of a system to proposed action. (See also Mathematical Model).

Sodium absorption ratio (SAR).--$Na/\sqrt{\frac{(Ca + Mg)}{2}}$ where the elements are expressed in millequivalents per liter.

Specific capacity.--For a producing well, the flow rate per unit of drawdown in the well.

Specific yield.--The volume of water that can be drained by gravity by a saturated rock or soil in relation to the volume of the rock or soil, including interstices.

Storage coefficient.--The volume of water released from storage or taken into storage in an aquifer, per unit surface area of the aquifer, per unit change in head.

Stream-aquifer system.--A stream and adjacent aquifer that are hydraulically connected, so that interchanges of water between the stream and aquifer will occur.

Stream depletion.--Reduction of streamflow in a stream-aquifer system due to withdrawals from wells that capture streamflow or intercept ground water that would have discharged to the stream.

Streamline.--In steady ground-water flow, may be regarded as a flow path.

Transmissivity.--The rate at which ground water may be transmitted through a cross section of unit width over the entire thickness of an aquifer, under standardized conditions. Equal to hydraulic conductivity multiplied by the thickness of the aquifer.

Unconfined aquifer.--An aquifer that has a water table and contains ground water that is not confined under pressure by overlying impermeable or significantly less permeable material.

Underflow.--Downstream movement of ground water in a valley-fill aquifer.

Water table.--The imaginary surface within an unconfined aquifer at which the pressure is atmospheric. In usual practice, the water table is equivalent to the ground-water level in wells in an unconfined aquifer.

Synopsis

This is the final report to the International Poplar River Water Quality Board from the Ground Water Quantity and Quality Committee. The report presents and discusses the results of the committee's review of pre-existing and newly acquired information concerning ground water in the Poplar River Basin. It provides estimates based on ground-water modeling analyses and other techniques of the long-term quantity and quality effects of the Saskatchewan Power Corporation's (SPC) operation of a 600-megawatt power plant near Coronach, Saskatchewan. The estimates deal with the modifications in the natural ground-water system that are expected to result from: (1) dewatering of the Hart coal seam and overlying aquifers, (2) filling and operation of Cookson Reservoir, and (3) operation of the ancillary plant facilities such as the ash lagoons, coal piles, sewage lagoons, sod farms, cooling water return channel, and machine-shop and other maintenance operations. The estimates also deal with discharges from the ground-water system into rivers and streams of the Poplar River Basin and the long-term quantity and quality changes that might be expected to occur in these discharges as a result of power generation at Coronach.

The committee's work was based primarily on an appraisal of data and information already available from a variety of sources. A consultant collected and collated those data and information available for Saskatchewan. Copies of the final versions of the consultant's interim and final reports are on file with the agencies represented on the Ground Water Quantity and Quality Committee. New data obtained as a result of committee activities included (1) chemical analyses for a number of ground-water and surface-water samples collected at selected locations within the East Poplar River Basin, and (2) test-hole and aquifer test data from a number of new wells located at selected sites in the East Poplar River Basin of northern Montana. The new ground-water chemical quality data established the general reliability of earlier analyses as indicators of true ground-water chemical quality; they also served to point out earlier analyses that were obviously in error and should be rejected. The new test holes provided information on the continuity and hydraulic properties of the Hart coal seam south of the International Boundary; they will also provide critical observation points for monitoring ground-water quantity and quality changes resulting from the generation of thermal power at the Coronach plant.

The complexity of the ground-water system underlying the Poplar River Basin dictated the use of mathematical models for computer simulation of total-system behavior under the influence of Saskatchewan Power Corporation power-generation activities. Two such models were utilized: (1) a finite-element model designed to evaluate the combined effects of dewatering and natural recharge by precipitation and (2) a finite-difference model designed for the estimation of water-level changes in a five-layered aquifer system. In the second model the five layers represented the complete stratigraphic sequence down to the top

of the Bearpaw Formation or shale which was considered to be sufficiently impermeable to be taken as a lower boundary to the flow system. While the second model considered the effects of dewatering and the operation of Cookson Reservoir, the effects of ancillary facilities were estimated by more simplified procedures as outlined in the succeeding paragraph. Both mathematical models were representative of an area roughly equivalent to that occupied by the East Poplar River Basin. This area includes all parts of the Poplar River Basin in which significant ground-water quantity and quality effects may reasonably be expected.

The ancillary facility of greatest concern in terms of water contamination is the ash lagoon area. A simplified approach was adopted in order to evaluate its possible effects: one-dimensional subsurface vertical flow was assumed from the ash lagoons to a horizontal and highly permeable sand and gravel bed. Subsequent one-dimensional horizontal flow was assumed through the permeable bed to discharge into the East Poplar River below Morrison Dam. These assumptions plus several others involved in the estimation of the ash-lagoon effects combined to make this evaluation an extreme or "most severe" case.

None of the other ancillary facilities was examined in the same detail as were the ash lagoons, but the ash lagoon evaluation provided a convenient yardstick for speculation on other effects. Predictions derived from the mathematical models or from the simplified ash lagoon analysis related to predictions of ground-water chemical-quality changes, presumed that many of the chemical parameters are conservative. In other words, it was assumed in these cases that there are no sorption, ion exchange, precipitation or other processes that significantly retard the movement of ions in comparison with the movement of ground water.

Conclusions from the study are conveniently arranged into three categories: (1) baseline conditions and recent changes, (2) predicted long-term quantity changes, and (3) predicted long-term quality changes. They are presented in detail in the conclusions section of this report and only a partial summary of the more important findings is presented here:

(1) Under natural conditions the chemical quality of ground water in formations lying below the glacial and preglacial deposits often exceeds the recommended levels for iron, manganese, nitrate, non-ionized ammonia, phenols, copper, fluoride, sodium absorption ratio, sulfate, zinc and selenium. Local high concentrations of uranium and selenium are possible in the vicinity of uranium-roll deposits, which may occur in the deposits overlying the coal seam.

(2) Up to the present time there have been no transboundary quantity or quality impacts to ground water as a result of mine dewatering operations.

(3) The predicted maximum drawdown of water levels in the upper Fort Union aquifer of Montana (upper Ravenscrag in Saskatchewan) is 0.7 m near the International Boundary after 35 years of dewatering. The predicted maximum rise in water level after 75 years of reservoir leakage is 0.1 m near the International Boundary.

(4) Surface-water depletion caused by the modification of the ground-water flow system during dewatering and the operation of Cookson Reservoir will be much more pronounced in Saskatchewan than in Montana. Maximum predicted streamflow depletion in Montana is only 100 m^3/d for Goose Creek; predicted depletion for the East Poplar River in Montana is only 25 m^3/d.

(5) It is predicted that the quality of ground water moving across the International Boundary will not be degraded as a result of the SPC power plant operation. The size and number of saline-affected areas may increase in Montana because of the water-table rise due to the continuing leakage of water from Cookson Reservoir.

(6) The location of the ash lagoons as currently proposed present a high potential for contamination of both ground and surface water. There are similar but lesser hazards associated with leakage to ground water from other ancillary facilities.

(7) The chemical quality of ground water discharging to the East Poplar River below Morrison Dam will be affected by the seepage out of Cookson Reservoir passing below and around the dam, by the ash-lagoon leakage. The reservoir seepage water could eventually become similar in quality to the reservoir water; the ash-lagoon leakage is likely to be of poor quality.

(8) The chemical quality of water in bank storage in the alluvial deposits adjacent to the East Poplar River below Morrison Dam will probably become similar to the average quality of water in the river. If the water quality of the river is determined by releases of poor-quality water from Cookson Reservoir, the poor-quality water will be retained temporarily as bank storage until the stored water is gradually returned to its stream as the storage declines.

Consideration of the study findings led the committee to make a number of recommendations. The recommendations concern the following broad topic areas: (1) prevention or minimization of ground-water contamination, (2) monitoring, (3) review of validity of the mathematical ground-water models and (4) a mechanism for future monitoring and review. As was the case for the preceding presentation of the conclusions, the recommendations as presented here in the report synopsis are an abridged and consolidated summary of the more important issues.

(1) If the ash lagoons are located as proposed they should be lined with relatively impermeable material. Other ancillary facilities should be located on natural low-permeability, fine-grained soils or should be lined in the same way as the ash lagoons.

(2) Water levels in selected wells in northern Montana near the

International Boundary should be monitored on a periodic basis in order to detect changes due to dewatering or to operation of Cookson Reservoir. Water levels also should be monitored near the reservoir and a number of observations wells should be selected to observe natural ground-water level fluctuations.

(3) Dewatering well discharge rates should continue to be regularly measured and recorded.

(4) A comprehensive, accurate and reliable set of baseline ground-water chemistry data should be collected before power generation begins at the SPC Coronach plant. The data should include at least three complete samplings, one of which has already been completed (1976) and a second which should be carried out before the end of October 1978.

(5) Ground-water chemical quality should be monitored regularly in selected wells and piezometers to: (a) detect any movement of contaminated ground waters southward towards the International Boundary, (b) detect any movement of ash-lagoon leachate through the subsurface towards the East Poplar River and (c) detect any contamination of shallow aquifers in the vicinity of Cookson Reservoir.

(6) The first reclaimed mined areas should be surveyed to determine any changes in ground-water chemical quality within and adjacent to the reclaimed areas. Action should be taken, if appropriate, to modify mining and reclamation procedures in order to alleviate quality problems.

(7) Accurate estimates of leakage from Cookson Reservoir into the ground-water system are essential for determining ground-water budgets. Therefore water budgets based on continuous measurements of surface-water inflow, precipitation, and so forth should be prepared on a regular basis and used to estimate leakage.

(8) Ground-water model predictions were based on certain assumptions concerning aquifer-stream interactions, dewatering rates and the water level in Cookson Reservoir. Major deviations from these assumptions could invalidate model predictions. Interpretation of data from future monitoring activities should consider the effects of such deviations.

(9) An impartial review board should be created for the continuing monitoring and review of ground-water quality effects of the SPC power plant at Coronach.

Introduction

This report is concerned with the ground-water resources and the interrelationships between ground and surface waters in the Poplar River Basin, Saskatchewan--Montana. It addresses directive number 3, subsection 6, of the International Joint Commission of the International Poplar River water Quality Board regarding the Saskatchewan Power Corporation (SPC) Power Plant near Coronach, Saskatchewan. The directive reads in part:

> ". . . In this regard the Board shall examine into and report upon . . . significant transboundary impacts of the SPC's thermal power station and ancillary facilities, including coal mining, and of reasonably foreseeable developments in either country on the water quality and water level in the surrounding aquifers."

The report has been prepared by the Ground Water Quantity and Quality Committee (GWQQC) of the International Poplar River Water Quality Board (IPRWQB). In accordance with the directive cited above, the report is concerned with the ground-water related effects in Montana of the power development and associated facilities in Saskatchewan. Effects in Saskatchewan, except where they in turn lead to effects south of the International Border, have not been the concern of this committee.

Ground water is an important resource in the Poplar River Basin. It is used for domestic and municipal purposes, and is the main source of water to the Poplar River during low-flow periods. Many ranches and houses in the area depend upon ground water for their water supplies. Coronach, Saskatchewan (Fig. 1) uses both surface and ground water, whereas Scobey, Montana depends upon ground water exclusively.

Prior to the construction of the SPC Power Plant the only development of the ground-water resource in the Poplar River Basin was for domestic, stock, and municipal wells. The deepest wells in the basin extended to 110 m (meters). Most wells, however, are shallow, often less than 25 m in depth and are completed in shallow aquifers. Few data on the ground-water resources in the basin were available prior to the location of the SPC Plant near Coronach.

The SPC through its consultants has drilled a number of test wells and has collected a number of water samples for chemical analysis. Lignite beds and overlying formations are aquifers and must be dewatered prior to lignite removal by surface mining. This dewatering process has been under way since May 1976. The water removed from the lignite beds is channeled into Girard Creek and then into Cookson Reservoir, the SPC cooling-water impoundment. This water thus becomes an additional source of water for the operation of the power plant.

Test wells drilled by the SPC during plant development were an invaluable source of information for the study by the GWQQC.

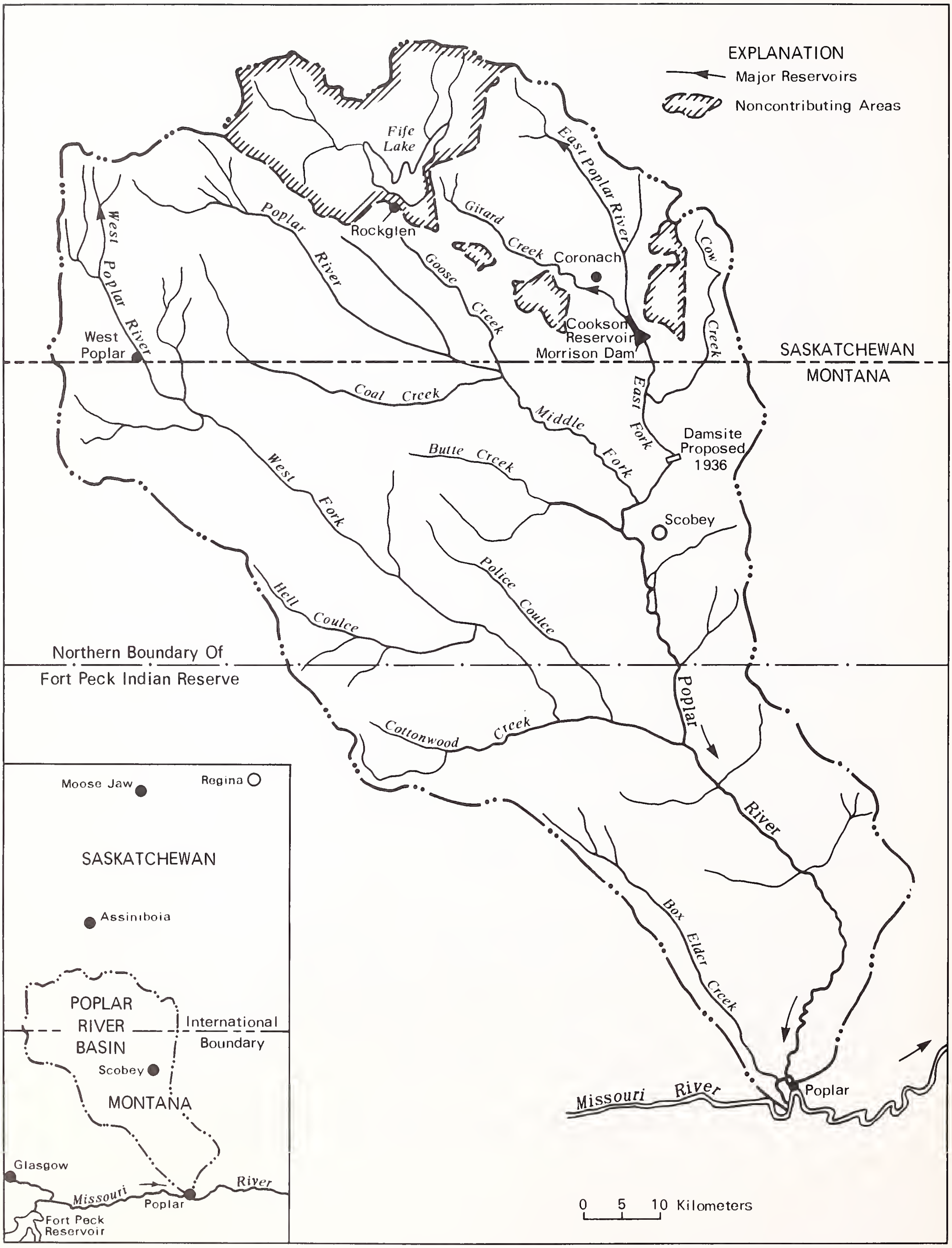


Figure 1.--Maps of Poplar River Basin, Saskatchewan-Montana.

Unfortunately, there were no similar test wells available in the Poplar River Basin in Montana prior to the study period. Since this GWQQC study began, 10 new test wells have been drilled at selected locations near the International Border and in Montana. Two of these wells were used to conduct aquifer tests of the coal aquifer in Montana. The 10 wells also will be used for future water-level measurements and for obtaining water for chemical analyses. The drilling and testing program was conducted using equipment and personnel provided by SPC and the Montana State Department of Highways.

Ground-water data for this study were primarily obtained from SPC records and from a reconnaissance study by Feltis (in preparation) who has made measurements at selected wells in Montana. Existing data and reports for Saskatchewan, particularly for the mine property and vicinity, were collected and collated under contract by Silverspoon Research Consulting, Ltd. Final versions of the Silverspoon reports are on file with the agencies represented by the GWQQ.

Chemical data for the study were obtained from SPC records and studies by the U.S. Geological Survey (Feltis, in preparation) and the Montana Bureau of Mines and Geology. Most of the chemical quality studies for the basin in Montana were supported by the U.S. Environmental Protection Agency (EPA). In particular, as a part of the present study, the GWQQC received financial support from the EPA for the analysis of water samples collected in May 1978 and from 19 additional ground- and surface-water sites in both Saskatchewan and Montana.

This report examines the flow and chemical characteristics of the ground-water system in the Poplar River Basin. Changes in flow characteristics resulting from the SPC power plant development and their resulting effects on surface-water systems are simulated by two mathematical models. The corresponding chemical characteristics were conceptually tied to the hydrologic flow models.

Acknowledgments

The GWQQC is grateful for the assistance provided by B. W. Graham and R. E. Jackson, Hydrology Research Division, Environment Canada, Ottawa in defining the ground-water contamination potential of the ash lagoons and other ancillary facilities. Mr. Jackson and K. J. Inch, Hydrology Research Division, Chalk River, Ontario ably assisted with geochemical model computing. Appreciation also is extended to Steven P. Larson of the U.S. Geological Survey, Reston, Virginia for advice and consultation in the design of the finite-difference ground-water model. The Committee also thanks David B. Grove for advice regarding solute transport modeling.

The cooperation and assistance of the staff of the Saskatchewan Power Corporation were essential to the GWQQC. In addition to providing free access to their files, they also kindly agreed to drill additional

test holes at strategic locations near the Montana-Saskatchewan border. The efforts of Wayne Nordquist, M. H. Allan, R. Hanson, Gary Pasloske, and Wayne Anderson of the SPC are particularly appreciated. Vince Beckie, Beckie Hydrogeologists--the corporation's hydrogeological consultant--was also most helpful, as was W. Chan of Keith Consulting Engineers. A number of people were involved in selecting sites for these wells and aquifer testing. Particular appreciation is extended to Richard D. Feltis, U.S. Geological Survey, Billings, Montana, and Joseph J. D'Lugosz, U.S. Geological Survey, Denver, Colorado. Information on the geology of the study area as well as the location of significant areas of interest was kindly provided by Robert Colton of the U.S. Geological Survey, Denver, Colorado. Numerous reports describing ground-water aquifer properties in Saskatchewan were provided by Mr. Ted Rey, Environment Saskatchewan. The hydrologic characteristics of aquifers listed in Table 5 were derived from these reports.

Description of Study Area

General

The Poplar River Basin includes parts of Saskatchewan in Canada and parts of Montana in the United States as shown in Figure 1. Principal streams in the basin include the West Poplar River (West Fork in Montana), Poplar River (Middle Fork), and East Poplar River (East Fork). These rivers drain parts of Saskatchewan and Montana and are tributary to the Missouri River near Poplar, Montana. Parts of the basin near Fife Lake and areas to the southeast have internal drainage and normally do not contribute to surface runoff. Morrison Dam as constructed by the SPC in 1976 on the East Poplar River and the resulting Cookson Reservoir is the principal storage reservoir in the basin.

Geology

Four principal geologic terrains in and adjacent to the study area combine to form a complicated physiography. The four terrains are: (1) alluvial river valleys; (2) widespread rolling uplands underlain by sand, silt, clay, and coal of bedrock formations; (3) gravel terraces; and (4) parts of the river valleys and adjacent uplands that are covered with glacial deposits.

Geologic units important to this study include bedrock and unconsolidated deposits. A brief description of geologic formations in Saskatchewan and Montana is shown in Table 1. The 10 test holes drilled near the International Border and in Montana confirmed the presence of the geologic units in the study area in Montana where geologic logs were generally not available. Formations that lie deeper than the Bearpaw were not considered because they are too deep to be affected by the operation of the SPC power plant.

The formations listed in Table 1 range in geologic age from Cretaceous (Bearpaw) to Holocene (alluvium). The Hart coal seam is of Tertiary age; deposited about 60 million years ago. A generalized geologic map of part of the upper Poplar River Basin is shown in Plate 1. The Frenchman (Hell Creek and Fox Hills) and Bearpaw are not exposed at the land surface within the study area.

Table 1.--Generalized Stratigraphic Column of Geologic Formations in Poplar River Basin

Formation (Saskatchewan)	Formation (Montana)	Range in thickness (m)	General character
Alluvium	Alluvium	0-55	Flood-plain deposits of gravel, sand, and silt.
Glacial deposits	Glacial deposits	0-30	Unconsolidated till, lake deposits, and glaciofluviatile deposits.
Empress Group	Wiota Gravels	0-3	Gravel.
Wood Mountain Formation	Flaxville Formation	0-30	Sand and sandy gravel.
Ravenscrag Formation, including Hart coal seam.	Fort Union Formation	50-245	Sandstone, siltstone, clay and lignite.
Frenchman Formation	Hell Creek Formation Fox Hills Sandstone	40-75	Sandstone, siltstone, and shale.
Bearpaw Formation	Bearpaw Shale	335-365	Shale and minor sandstone beds.

Land Reference System

The method of land subdivision is similar for both Saskatchewan and Montana except that in Saskatchewan, the sections within a township are numbered starting from the southeast rather than the northeast corner and each section is subdivided into 16 legal subdivisions starting with the southeast corner. The two systems are illustrated in Figures 2 and 3.

Saskatchewan

The system of numbering wells, springs, and sites in Saskatchewan (and in western Canada generally) is based on the rectangular grid system for land subdivision (Fig. 2 and Plate 1). A land description may consist of as many as 14 characters giving the land location within a given subdivision, section, township, and range. Townships are numbered consecutively westward from certain reference meridians of longitude. The first character in a complete land description is reserved for the well number within the legal subdivision, the next four are used to identify the legal subdivision and (if known) a specific quadrant within it, and the remainder identify section, township, range, and meridian. Quite commonly, the legal subdivision cannot be specified and the location may then be given as within a certain quadrant of a specified section (see for example Table 2).

Montana

The system of numbering wells, springs, or sites in Montana is based on the rectangular system for the subdivision of public lands (Fig. 3 and Plate 1). The location may consist of as many as 13 characters and is assigned according to its location within a given township, range, and section. The first three characters consist of the township number and the letter N or S designating position north or south of the Montana base line. The next three characters consist of the range number and the letter E or W designating position east or west of the Montana principal meridian. The next two characters indicate the section. The letters following the section number indicate the position of the well within the section. The first letter denotes the quarter section (160-acre tract); the second, the quarter-quarter section (40-acre tract); the third, the quarter-quarter-quarter section (10-acre tract); and the fourth, the quarter-quarter-quarter-quarter section (2.5-acre tract). The subdivisions of the section are lettered A, B, C, and D in a counterclockwise direction beginning in the northeast quarter. If two or more wells, springs, or sites are located within a 2.5-acre tract, consecutive numbers are added in the order of inventory within that tract. For example, well 37N48E08CDCC2 is the second well inventoried in the SWSWSESW Section 8, T 37 N, R 48 E.

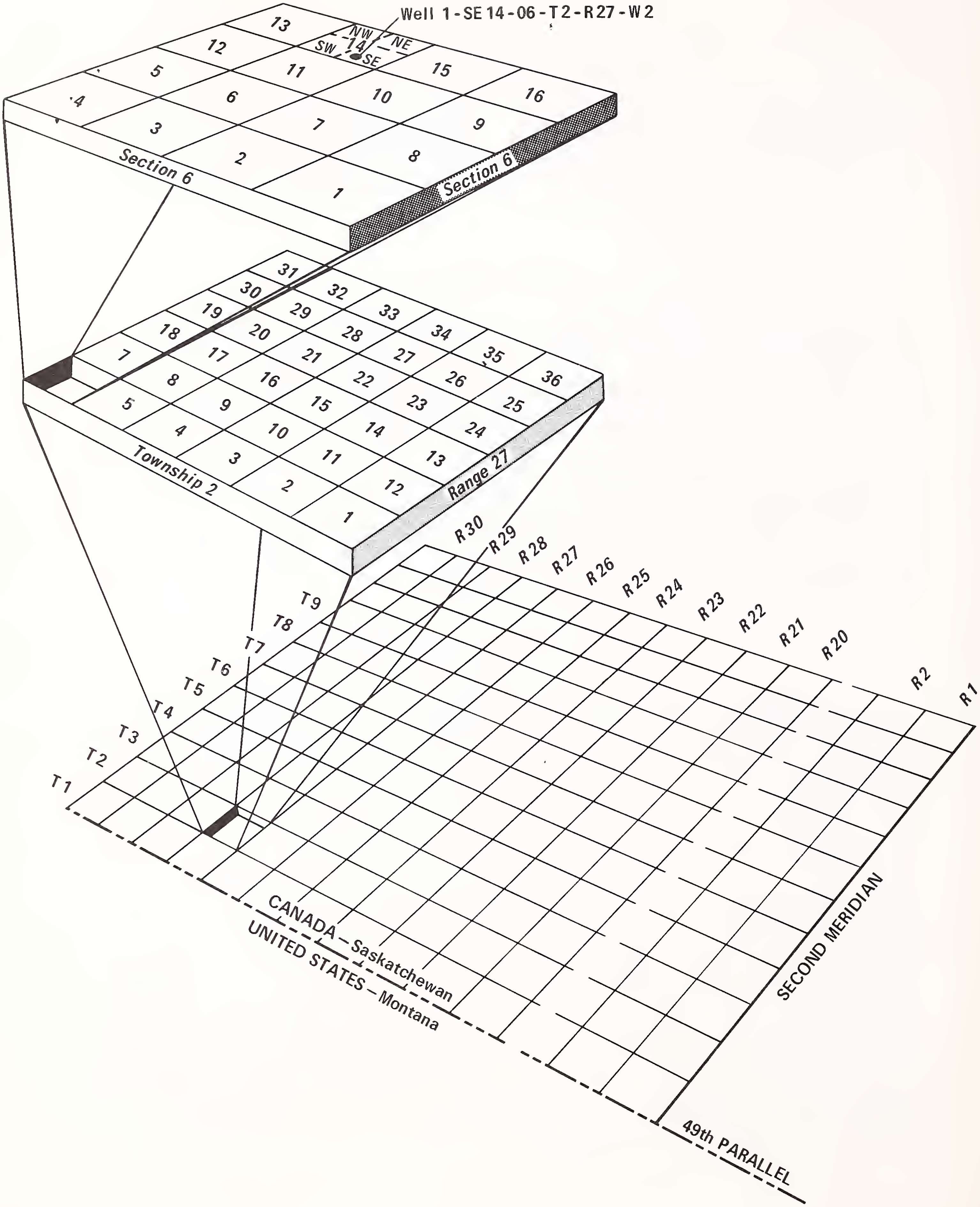


Figure 2.--Well, spring, and site numbering system for Saskatchewan.

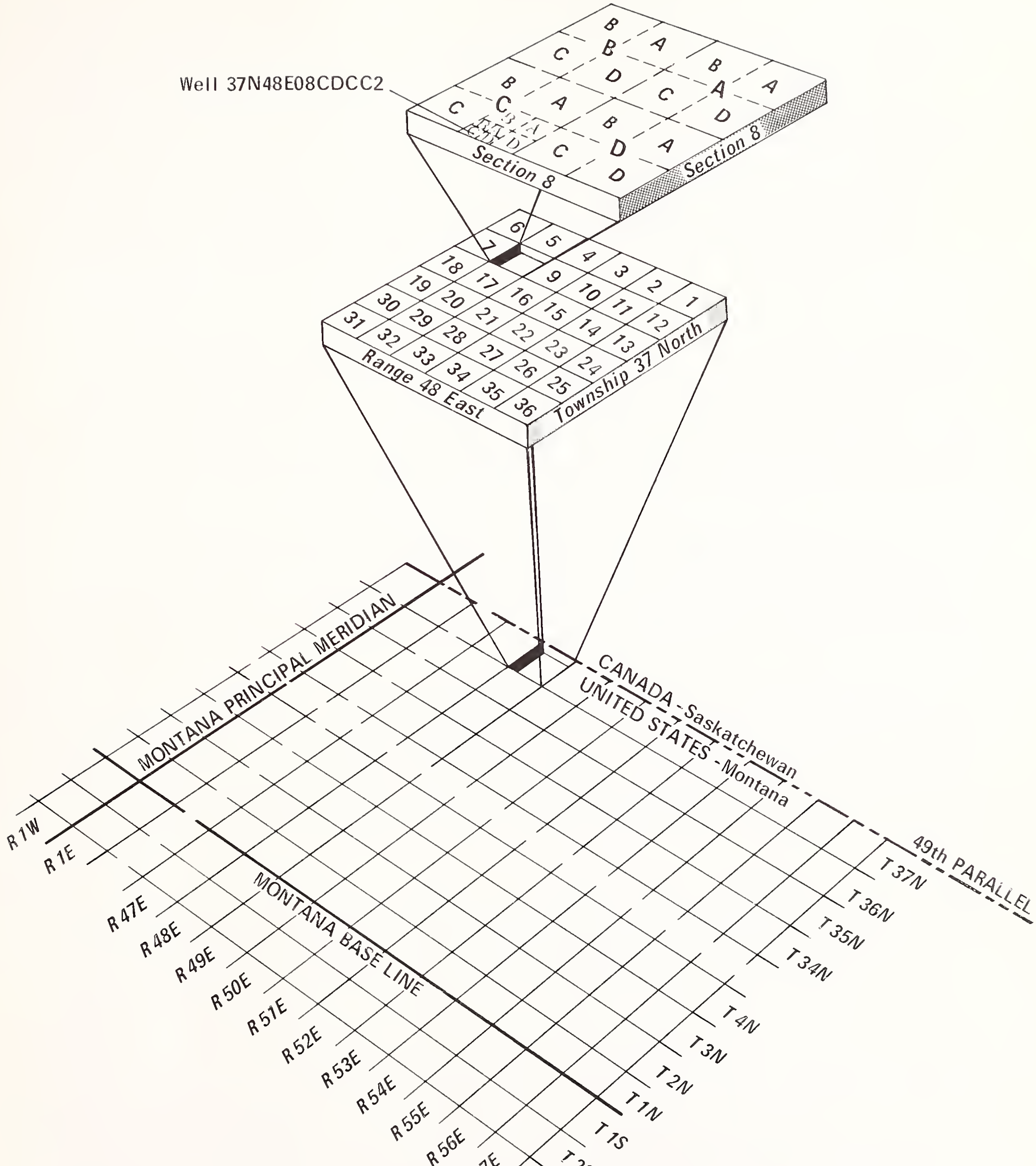


Figure 3.--Well, spring, and site numbering system for Montana.

Sources Of Data And Information

Data and information utilized for this report were made available from several sources. In the Saskatchewan part of the basin, most of the data originated with the SPC, through studies and investigations carried out by its consultants. Some of the preliminary geology in this part of the basin was mapped by the Saskatchewan Research Council prior to the initiation of the project. More detailed geological information was obtained as a result of the SPC coal investigation, dewatering program, and water-level monitoring installations. The Saskatchewan Department of the Environment made available its records of aquifer tests using municipal wells, together with data on existing water wells in the region.

As mentioned, the SPC provided numerous (in excess of 20) engineering reports prepared by the consultants. These reports described the geology, potential coal reserves, ground-water hydrology, water quality, water-level fluctuations, mine-site dewatering, and aquifer test results. They also provided base maps for the area as well as the SPC long-term development plans. The SPC further provided a two-volume Poplar River Reservoir Assessment report relating to operations and future plans.

The hydrogeologic framework of the area has been discussed in numerous published and unpublished reports issued by the Saskatchewan Research Council. The council supplied other data and was responsible for establishing the initial regional water-level monitoring program in the area.

As a depository for all hydrogeological data collected in the province, the Saskatchewan Department of Environment provided the GWQQC with available information and reports (such as well inventories, aquifer test results, and well drillers' reports). The Department of Environment also is cooperating with other agencies and consultants to develop additional comprehensive data-collection programs in the Poplar River Basin.

In the Montana part of the Poplar River Basin, geological and hydrological information was obtained from the U.S. Geological Survey and the Montana Bureau of Mines and Geology. Because of the sparsity of some types of data, the GWQQC collected additional information during the study period.

Several early geologic investigations in the Montana part of the study area were conducted by the U.S. Geological Survey. Recent hydrogeological information was provided by R. D. Feltis of the U.S. Geological Survey in cooperation with the U.S. Environmental Protection Agency and the Montana Bureau of Mines and Geology. The Montana Bureau of Mines and Geology also made available published and unpublished hydrogeologic data.

Available information on both sides of the International Border was collated for the GWQQC by the firm of Silverspoon Research and Consulting, Ltd. The GWQQC also solicited the advice of R. D. Feltis and R. B. Colton of the U.S. Geological Survey on matters relating to the study area.

As stated earlier, the GWQQC initiated a program to collect supplemental information. The program consisted of the drilling and logging of 10 test holes totaling about 670 m, conducting two aquifer tests, and collecting and analyzing 19 water samples. The test-hole data are available at Montana Bureau of Mines and Geology, and the chemical-quality data can be obtained in the United States from the U.S. Geological Survey WATSTORE, or U.S. Environmental Protection Agency STORET data systems, and in Canada from the NAQUADAT data bank through the Inland Waters Directorate, Environment Canada. The well and test-hole information and water sample locations are summarized in Figure 4 and Tables 2 and 3.

Table 2.--Location of New Test Holes and Observation Wells Drilled Between May 22 and June 9, 1978

Field reference No.	Location*	Total depth (m)	Casing size and type	Remarks
GWQQC-1	36N48E2BABB	90	38 mm PVC	Coal bed absent
GWQQC-2	37N47E17DABB	115	38 mm PVC	3.0 m coal bed
GWQQC-3	37N47E23AADD	165	38 mm PVC	3.0 m coal bed
GWQQC-4	37N48E23BBCC	120	38 mm PVC	Coal bed absent
GWQQC-5	37N47E1ABBB1	16	102 mm PVC	Aquifer test
GWQQC-6	37N47E1ABBB2	25	102 mm PVC	2.4 m coal bed
GWQQC-7	37N47E12BBBB	45	102 mm PVC	2.4 m coal bed
GWQQC-8	37N47E13AADD1	14	102 mm PVC	Aquifer test
GWQQC-9	37N47E13AADD2	63	102 mm PVC	Coal bed absent
GWQQC-10	37N48E5BABB	13	102 mm PVC	1.5 m coal bed

*For explanation see section on Land Reference System.

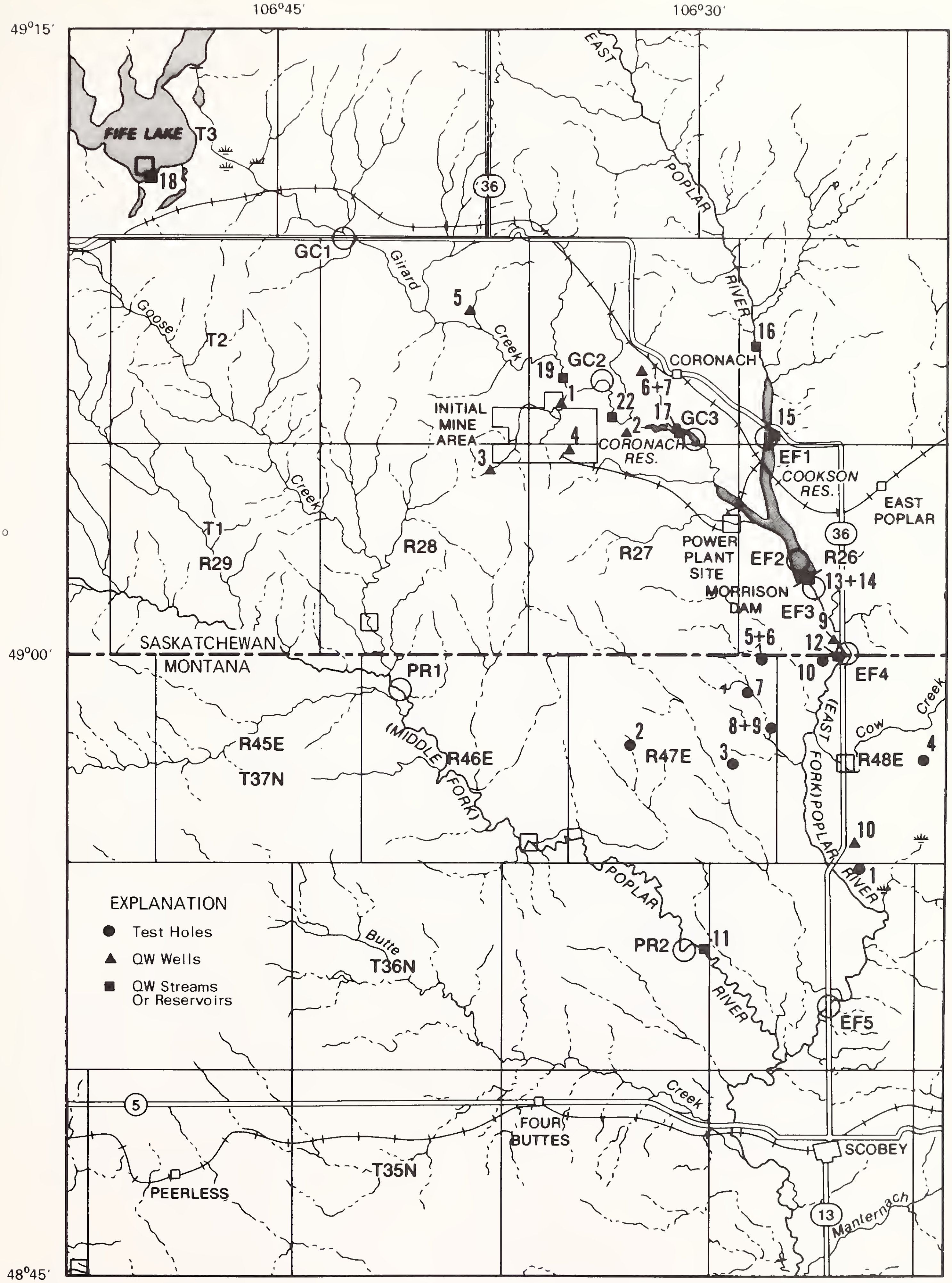


Figure 4.--Map showing locations of new data-collection sites (1978).

Table 3.--Location of Chemical Quality Sampling Sites, May 1978
[Sample sites 8, 20, and 21 were duplicates of sites 2, 9, and 18, respectively.]

Field reference No.	Location*	Latitude	Longitude	Remarks
GWQQC-QW1	SE7-2-27-W2	490620	1053517	Mine dewatering well #PW1
GWQQC-QW2	SE4-2-27-W2	490527	1053242	Mine dewatering well #PW11
GWQQC-QW3	SE35-1-28-W2	490438	1053820	Domestic well; Frenchman Formation.
GWQQC-QW4	NW32-1-27-W2	490512	1053512	Domestic well; glacial deposits.
GWQQC-QW5	NW23-2-28-W2	490838	1053840	Domestic well; Hart coal seam.
GWQQC-QW6	SW15-2-27-W2	490658	1053116	Domestic well; Ravenscrag Formation above Hart seam.
GWQQC-QW7	SW15-2-27-W2	490657	1053114	Domestic well; Ravenscrag Formation below Hart seam.
GWQQC-QW9	SW3-1-26-W2	490001	1052429	Domestic well; Frenchman Formation.
GWQQC-QW10	37N48E33BDC	485507	1052409	Domestic well; glacial deposits.
GWQQC-QW11	36N47E13D	485200	1052950	Poplar River
GWQQC-QW12	37N48E5AAA	485957	1052431	East Poplar River at International Border.
GWQQC-QW13	SE17-1-26-W2	490136	1052556	Seep at toe of Morrison Dam.
GWQQC-QW14	SE17-1-26-W2	490138	1052554	Cookson Reservoir at Morrison Dam.
GWQQC-QW15	SE6-2-26-W2	490544	1052757	Cookson Reservoir at upstream end.
GWQQC-QW16	NW18-2-26-W2	490819	1052755	East Poplar River upstream of Cookson Reservoir.
GWQQC-QW17	SW2-2-27-W2	490516	1053026	Coronach Reservoir (municipal).
GWQQC-QW18	NW9-3-29-W2	491144	1055118	Fife Lake.
GWQQC-QW19	NE7-2-27-W2	490654	1053525	Girard Creek above mine dewatering discharge.
GWQQC-QW22	NW4-2-27-W2	490606	1053327	Girard Creek below mine dewatering discharge.

*For explanation see section on Land Reference System.

Hydrology

Ground-Water Flow Systems

Ground-water flow systems for the upper Poplar River Basin were analyzed in order to determine the natural recharge to, movement through, and discharge from various aquifers. Flow systems were studied by interpretation of geologic maps and potentiometric maps, by measurements of streamflow, and by observation of discharge from springs.

Potential recharge areas are indicated by permeable surficial deposits on the geologic map (Plate 1). Exposures of the Wood Mountain Formation in Saskatchewan and equivalent Flaxville Formation in Montana commonly consist of coarse, clean, permeable gravel. Deposits of valley-fill alluvium along streams and major tributaries also consist of permeable sand and gravel in many areas. Therefore, the exposures of Wood Mountain Formation, Flaxville Formation, and valley-fill alluvium shown on Plate 1 are probably the principal areas of natural recharge from precipitation. A potentiometric map for the shallow aquifers in the upper Poplar River Basin (Feltis, in preparation) is shown on Plate 2. Potentiometric heads on the map cannot be related to any specific aquifer because of the lack of well logs in the area. However, the high altitudes of the potentiometric surface coincide with exposures of the Flaxville Formation, and indicate that the Flaxville receives significant natural recharge from precipitation. Areally extensive potentiometric maps are not available for southern Saskatchewan, so the altitude of heads in the equivalent Wood Mountain Formation cannot be compared. Recharge to the valley-fill alluvium is not apparent on the potentiometric map because the alluvium is hydraulically connected to the streams. Recharge to the alluvium probably moves readily to the streams where it is discharged. Recharge to other aquifers is poorly understood.

Ground-water movement also is indicated by potentiometric maps. The general direction of movement is across the potentiometric contours in the down-gradient direction. The configuration of the contours on Plate 2 suggests that in northern Montana the natural recharge to the Flaxville Formation moves through the Flaxville and Fort Union Formations and into the valley-fill alluvium along streams and tributaries. The general trend of the contours in the stream and tributary valleys indicates that ground water in the valley-fill alluvium moves in the downstream direction as underflow.

The Hart coal seam is not continuous throughout the study area because it has been removed by erosion in the major stream valleys as shown in Plate 3. Coal horizon D described by Collier (1925) is the probable equivalent in Montana of the Hart coal seam in Saskatchewan. A potentiometric map for the Hart coal aquifer prior to plant development is shown in Plate 4 (Whitaker and Vonhof, 1978a). The potentiometric contours in Plate 4 are continuous across zones in which the Hart coal seam is absent, indicating that hydrologic continuity across the zones is maintained by adjacent permeable beds of the Empress Group and (or) glacial till. Ground-

water movement in the coal is generally toward the southeast, in the direction of surface drainage. In T1 R26 W2 of southern Saskatchewan, the ground-water movement converges toward the valley of the East Poplar River. The potentiometric surfaces of the Hart coal aquifer in southern Saskatchewan (Plate 4) and for the shallow aquifers in northern Montana (Plate 2) conform along the International Border, suggesting that the potentiometric surfaces are similar for all shallow aquifers in the study area. However, only a few potentiometric maps could be prepared because of limited field data.

A potentiometric map was prepared for the Frenchman aquifer in Saskatchewan and equivalent Fox Hills-basal Hell Creek aquifer of Montana (Whitaker and Vonhof, 1978b). The map, shown on Plate 5, indicates that ground-water movement is northeast, east, and southeast. The ground water converges toward the East Poplar River Valley near Scobey, Montana.

Ground-water discharge consists of springs that issue from several aquifers, flow from valley-fill alluvial aquifers to the stream system, and underflow out of the study area. Springs issue from the Wood Mountain Formation, Flaxville Formation, Ravenscrag Formation, and Fort Union Formation and partially discharge these aquifers. Valley-fill alluvial aquifers reportedly drain to the streams in Saskatchewan. A report by Feltis (in preparation) describes the results of a gain-and-loss study on streams of the Poplar River Basin in northern Montana where most reaches of the stream appear to be gaining. The average net gain to streamflow and ground-water discharge was about 7×10^3 m^3/d (cubic meters per day) on October 19-20, 1970. The downstream gradient of the potentiometric surface along the East Poplar River shown in Plate 2 indicates that underflow in the valley-fill aquifer flows to the south toward the Missouri River Valley. A general sketch of ground-water flow system is shown in Figure 5.

Aquifer Properties

The preceding description of the ground-water flow system of the upper Poplar River Basin provides a general understanding of the hydrologic behavior of this region. However, a more quantitative approach was required in order to provide needed data for the mathematical simulation models to be described later. Accordingly the hydrologic characteristics of the aquifers were estimated on the basis of information gained from a literature review and an evaluation of the few available aquifer measurements from the study area. For convenience in discussion and modeling, the aquifers were classified into five principal layers, numbered in ascending order as shown in Table 4. Layer 5 includes most unconfined units exposed at the land surface. The hydrologic characteristics of the various units included in layer 5 vary widely, but nowhere is any unit superimposed over any other, so each is considered separately. Layer 4 consists of sandstone, silt, clay, shale, and coal beds that constitute a confined aquifer. Layer 3 represents the confined permeable coal-seam aquifer that will be mined in Saskatchewan and

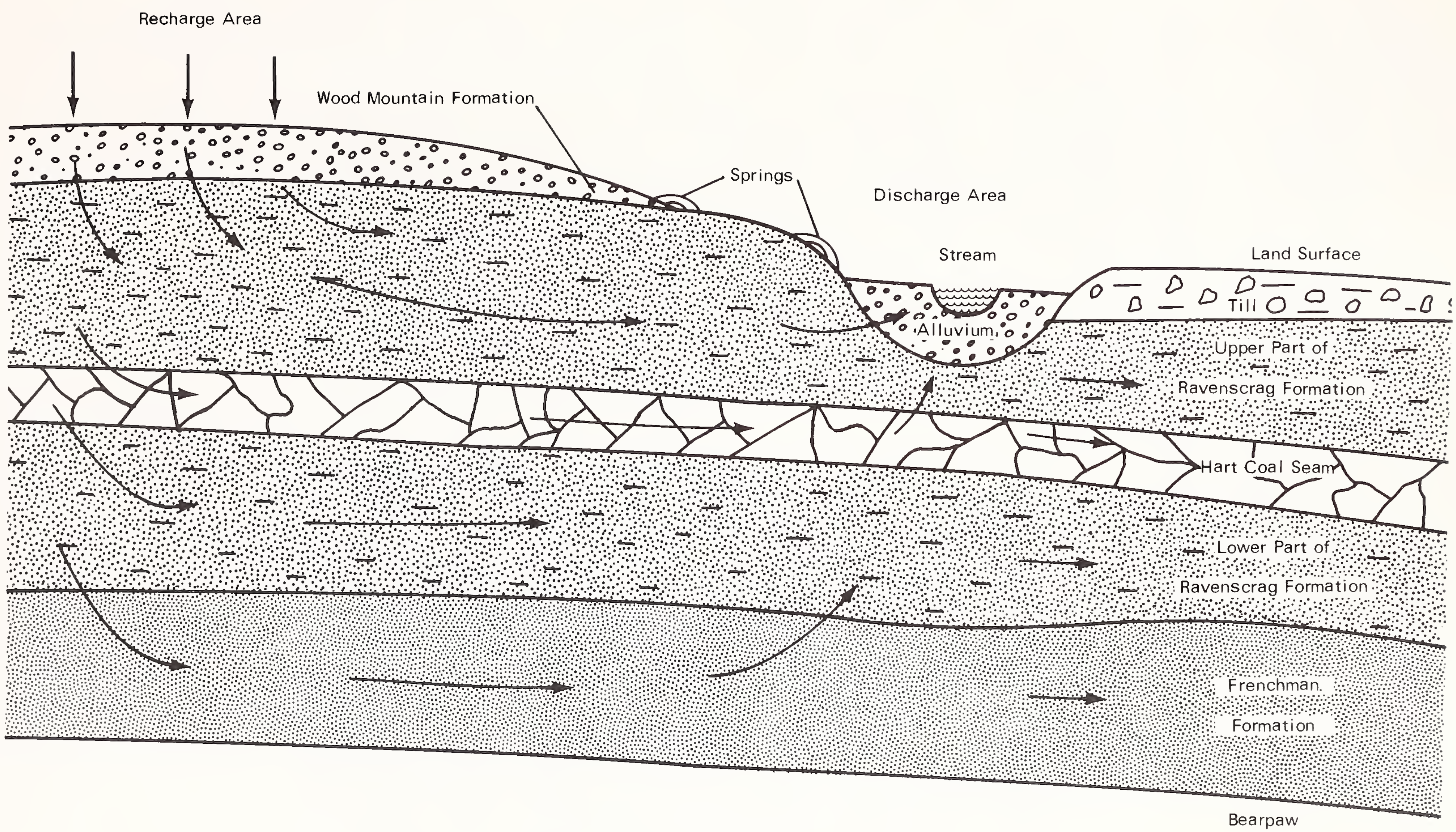


Figure 5.--Schematic diagram showing ground-water flow from recharge areas to discharge areas.

its probable stratigraphic equivalent in Montana. Layers 3 and 4 are absent in major stream valleys of the basin. However, in Girard Creek Valley deposits of the Empress Group and (or) glacial fill may provide hydraulic continuity of the layers across the valley. Layer 2 is similar lithologically to layer 4 and also is regarded as a confined aquifer rather than a confining layer. Layer 1 is the ubiquitous confined sandstone aquifer that lies directly above the Bearpaw Formation or Shale. Layers 1 and 2 are continuous over the upper Poplar River Basin.

Table 4.--Generalized Aquifer Layers of the Upper Poplar River Basin, Saskatchewan and Montana

Layer	Canada	United States
5	Valley-fill alluvium, glacial deposits, and Wood Mountain Formation	Valley-fill alluvium, glacial deposits, and Flaxville Formation
4	Upper Ravenscrag Formation	Upper Fort Union Formation
3	Hart coal seam	Lignite, horizon D (Collier, 1925)
2	Lower Ravenscrag Formation	Lower Fort Union Formation and upper Hell Creek Formation
1	Frenchman Formation	Lower Hell Creek Formation and Fox Hills Sandstone

Estimated hydrologic characteristics of each layer are shown in Table 5. Values of transmissivity, storage coefficient, and specific yield were taken from published reports or estimated. Mean horizontal conductivity was calculated by dividing mean transmissivity by mean aquifer thickness. Measured values of vertical hydraulic conductivity were unfortunately not available and, in fact, there is very little published information of any kind on vertical conductivities or conductivity) ratios (the ratios of horizontal to vertical hydraulic conductivity) for geologic deposits. Despite the lack of accurate data, it is generally accepted by hydrogeologists that layered rocks are usually more conductive parallel to the layering than perpendicular to it. The mathematical simulation model incorporating the estimated hydrologic characteristics presented in Table 5 was subjected to a sensitivity analysis that will be described later, in order to determine the changes in model results related to possible errors in hydrologic characteristics and model formulation.

Table 5.--Estimated Hydrologic Characteristics of Generalized Aquifer Layers of Upper Poplar River Basin, Saskatchewan and Montana

Layer		Saturated thickness (m)	Mean transmissivity (m^2/d)	Mean horizontal hydraulic conductivity (m/d)	Mean vertical hydraulic conductivity (m/d)	Ratio of horizontal hydraulic conductivity to vertical hydraulic conductivity	Storage coefficient or specific yield
5	Valley-fill alluvium----	0-60	4.7×10^{2}	4.4×10^{1}	4.4×10^{0}	10:1	2.0×10^{-1}
	Glacial deposits----	0-25	3.7×10^{-3}	3.5×10^{-4}	3.5×10^{-5}	10:1	5.0×10^{-2}
	Wood Mountain Formation and Flaxville Formation----	0-14	9.5×10^{1}	8.9×10^{0}	8.9×10^{-1}	10:1	2.0×10^{-1}
4		0-130	3.7×10^{1}	9.8×10^{-1}	9.8×10^{-4}	1,000:1	1.0×10^{-3}
3		0-5	5.0×10^{1}	2.0×10^{1}	4.0×10^{0}	5:1	4.0×10^{-3}
2		50	3.7×10^{1}	7.4×10^{-1}	1.9×10^{-4}	4,000:1	1.0×10^{-3}
1		60	7.4×10^{1}	1.2×10^{0}	3.0×10^{-4}	4,000:1	2.8×10^{-4}

The average thickness of layer 5 is about 11 m and the characteristics of each unit of layer 5 are tabulated separately. The transmissivity of the valley-fill alluvium near Scobey, Montana was estimated as 930 m^2/d (square meters per day) from a specific capacity test on a municipal well. Elsewhere the transmissivity is probably lower due to the smaller saturated thickness, except in the vicinity of Cookson Reservoir where the saturated thickness is approximately 60 m and the transmissivity may be higher. The mean vertical hydraulic conductivity was estimated as about one-tenth of the mean horizontal hydraulic conductivity because of the presumed effect of bedding planes in the alluvium on water movement. Specific yield of the alluvium is probably about 0.2, a reasonable value for unconfined deposits of sand and gravel.

The mean transmissivity of glacial deposits was estimated as 3.7×10^{-3} m^2/d. The value selected is higher than the normal transmissivity of glacial deposits of comparable thickness and lithology because of the presence of fractures that probably increase the transmissivity substantially. The ratio of horizontal to vertical hydraulic conductivity was estimated to be 10:1 because of occasional permeable beds along bedding planes. The specific yield of the glacial deposits was estimated to be 0.05, owing to the fact that although fractures allow relatively good hydraulic connection, the withdrawal of water from storage within the unfractured matrix will represent the most significant long-term storage effect for the glacial deposits.

Mean transmissivity of the Wood Mountain and Flaxville Formations was estimated as 95 m^2/d. The estimated ratio of horizontal to vertical hydraulic conductivity and the estimated specific yield for the aquifer are the same as for the valley-fill alluvium.

The hydrologic characteristics of layer 4 were partly measured and partly estimated. Average thickness of layer 4 is about 38 m. In North Dakota and Montana various measurements of transmissivity of the upper Fort Union aquifer range from about 6.2 to 50 m^2/d. An aquifer test of a 4.9-m sandstone bed of the Ravenscrag Formation was conducted by M. R. Hall Drilling, Ltd. for the town of Willow Bunch, Saskatchewan. Resulting determinations of transmissivity range from 30 to 78 m^2/d; values of the coefficient of storage range from 7.5×10^{-4} to 8.5×10^{-3}. The selected value of transmissivity for this analysis was 37 m^2/d and the coefficient of storage was estimated as 1.0×10^{-3}. The ratio of horizontal to vertical hydraulic conductivity was estimated as 1,000:1, considering: (1) the effect of barely pervious beds on reducing the overall vertical hydraulic conductivity of a heterogeneous and anisotropic layer (Harr, 1962), and (2) the effect of reported vertical fractures that would increase the overall vertical hydraulic conductivity.

The tranmissivity and storage characteristics of the 2.5-m aquifer, layer 3, were estimated from aquifer tests. Several aquifer tests of the coal were conducted in 1973 by J. D. Mollard and Associated, Ltd. near the southeast corner of section 7, T 2 R 27 W2 in Saskatchewan. Results of the tests were complex and indicated values of transmissivity

between 100 and 3,700 m^2/d. The relatively high values of transmissivity for the thin aquifer suggest severe fracturing and large openings. However, single-well tests on the coal aquifer were conducted in 1978 by the GWQQC in sections 1 and 12, T 37N R 47E in Montana. Transmissivity values ranged from 0.16 to 2.6 m^2/d and indicated that the coal aquifer is much less transmissive in this area. Apparently the large variations in coal transmissivity are primarily due to similar large variations in hydraulic conductivity because the aquifer thickness remains relatively uniform. Several of the single-well aquifer tests conducted in Saskatchewan in 1973 indicated a transmissivity of 100 m^2/d, the value that was selected as a maximum for the aquifer in the area of study. The ratio of horizontal to vertical hydraulic conductivity was estimated to be only 5:1 because fracture permeability becomes a much more significant factor for this layer. The aquifer tests conducted by J. D. Mollard and Associates, Ltd., indicated that the storage coefficient of the coal aquifer is approximately 1.0×10^{-2} to 2.0×10^{-2}. However, simulation studies described later in this report indicated that discharge from, or recharge to, the coal aquifer also affects other layers that were not considered in aquifer-test analysis. The storage coefficient of the coal is probably closer to 4.0×10^{-3}.

Layer 2, with an average thickness of about 50 m, is geologically and physically similar to layer 4. Therefore, most of the hydrologic characteristics of the two layers were estimated to be similar. The ratio of horizontal to vertical hydraulic conductivity was, however, an exception. This was estimated at 4,000:1 for layer 2 because of the relative absence of fractures in layer 2 compared to layer 4.

The hydrologic characteristics of layer 1 are more widely known in Saskatchewan and Montana than are those of the other layers. Average thickness of layer 1 is about 60 m. A transmissivity value of 75 m^2/day is reported by Saskmont Engineering (1978). An aquifer test was conducted in 1975 by J. D. Mollard and Associates, Ltd. in the southern part of section 25, T 1 R 27 W2 in Saskatchewan. Various interpretations of the aquifer test indicate a transmissivity between 8.1 and 26 m^2/d and a storage coefficient between 1.0×10^{-4} and 8.3×10^{-4}. The results of extensive testing of this aquifer in eastern Montana are reported by Taylor (1968). Estimated values for layer 1 are shown in Table 5 and were derived from all available data.

A flow-net analysis was made of parts of the potentiometric map in Plate 2 in order to provide a rough check on the values of transmissivity selected for several layers in Montana. Nineteen pairs of streamlines were drawn on the map at right angles to the potentiometric contours. The ground-water flow was presumed constant between each pair of lines; therefore, the local transmissivity is inversely proportional to the product of the local hydraulic gradient and the local distance between streamlines. Using this technique, it was possible to compare the relative transmissivities of the valley-fill and lower Fort Union aquifers; the valley-fill, lower Fort Union and Flaxville aquifers; and the lower Fort Union and Flaxville aquifers. By assuming that the transmissivity

of the valley-fill aquifer increases in the downstream direction, it was possible to construct a diagram of relative transmissivities as shown in Figure 6. Springs that issue from the Flaxville and lower Fort Union aquifers reduce the flow and distort the relative values. The true values of transmissivity of the Flaxville and lower Fort Union aquifers are probably near the minimum values shown. A comparison of the relative values of transmissivity in Figure 6 and the estimated values in Table 5 shows reasonable agreement.

Chemical Properties of Ground Water

The natural ground water in the study area is generally of marginal quality, and often exceeds recommended or mandatory limits of state, provincial, or federal governments for one or more chemical parameters. Other than ground water pumped for mine dewatering by the SPC, all ground water in the study area is used for municipal, domestic, or farm supplies. Therefore, in discussing the chemical quality of ground water the emphasis will be on its significance to humans and livestock, with a brief discussion on possible effects on irrigated crops. Considering the nine ground-water samples collected by the GWQQC in the study area, the following chemical parameters exceeded concentration criteria established by the Uses and Water Quality Objectives Committee (of the IPRWQB) in at least one well: iron, manganese, nitrate, unionized ammonia, phenols, copper, fluoride, sodium absorption ratio (SAR), sulfate, zinc, and selenium.

Although no similar criterion has been established for molybdenum, it should be noted that water from one well in the study area contained 10 μg/L molybdenum and two wells sampled in the Frenchman Formation had 5 μg/L molybdenum. The significance of high levels of molybdenum relates to the possible occurrence of molybdenosis, a disease of cattle caused by an imbalance in the copper-molybdenum ratio in their food and water (Erdman and Others, 1978). Since it is the value of the ratio rather than the absolute level of molybdenum that gives rise to molybdenosis, it is not possible to specify a level of molybdenum that should not be exceeded.

The chemical quality of ground water in the study area is variable. As shown in Figures 7 and 8, the water quality in a single well varies with time. Some of the variability in Figures 7 and 8 is because of analytical error, but the systematic changes probably are due to actual variations in chemical quality. Of much greater importance are the vertical and horizontal changes in chemical quality due to geochemical processes as shown diagrammatically in Figure 9. Even there, the concentrations do not represent extreme values for the study area. That is, even among the none ground-water samples collected in the area, variation was greater than shown in Figure 9. For example, calcium ranged from 0.2 to 22 me/L, sodium ranged from 0.06 to 29 me/L, iron ranged from 0.003 to 0.2 me/L, and boron ranged from 40 to 2900 μg/L. More detailed

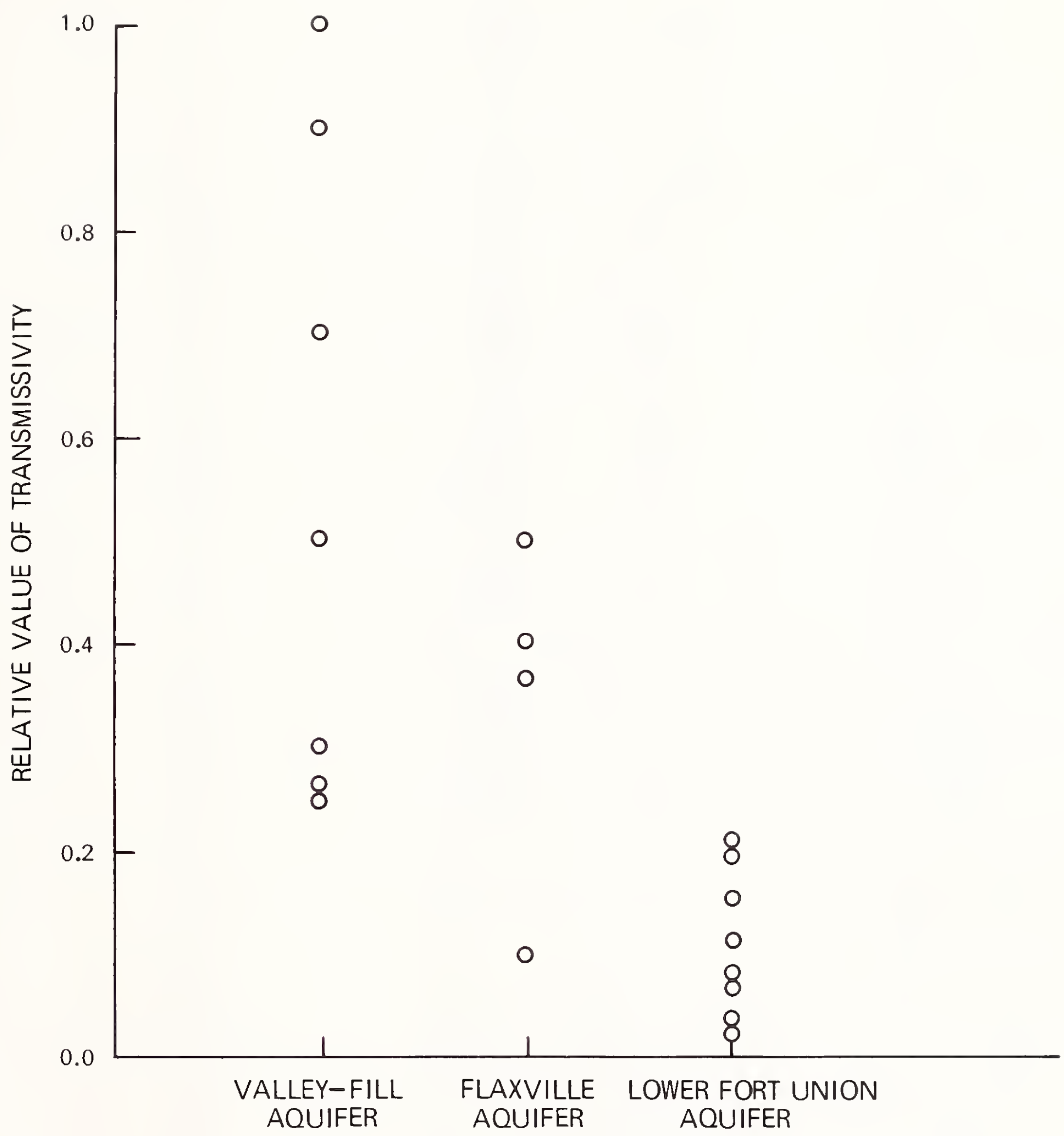


Figure 6.--Relative values of transmissivity for valley-fill, Flaxville, and lower Fort Union aquifers.

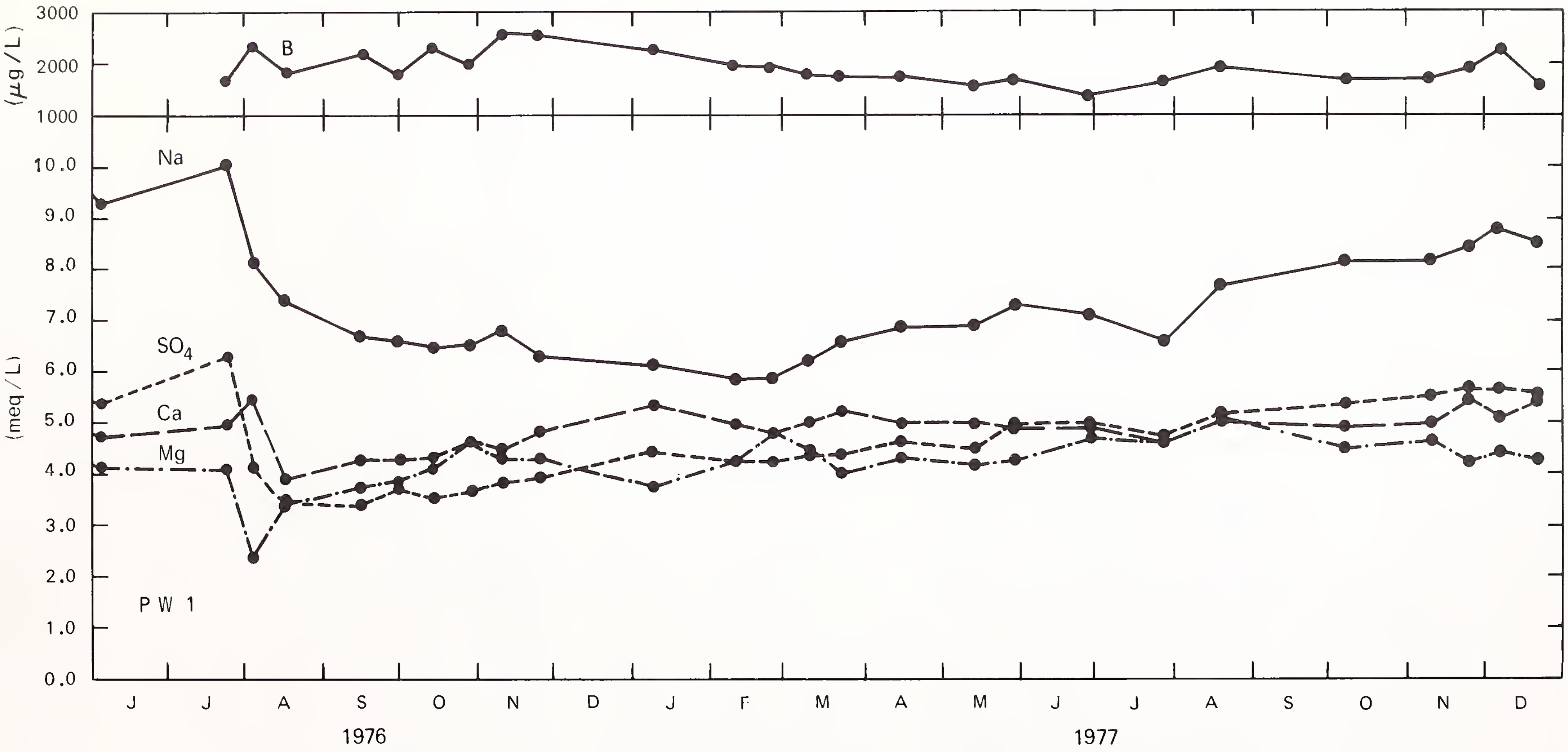


Figure 7.--Diagram showing temporal variations in selected chemical parameters in mine well Number 1.

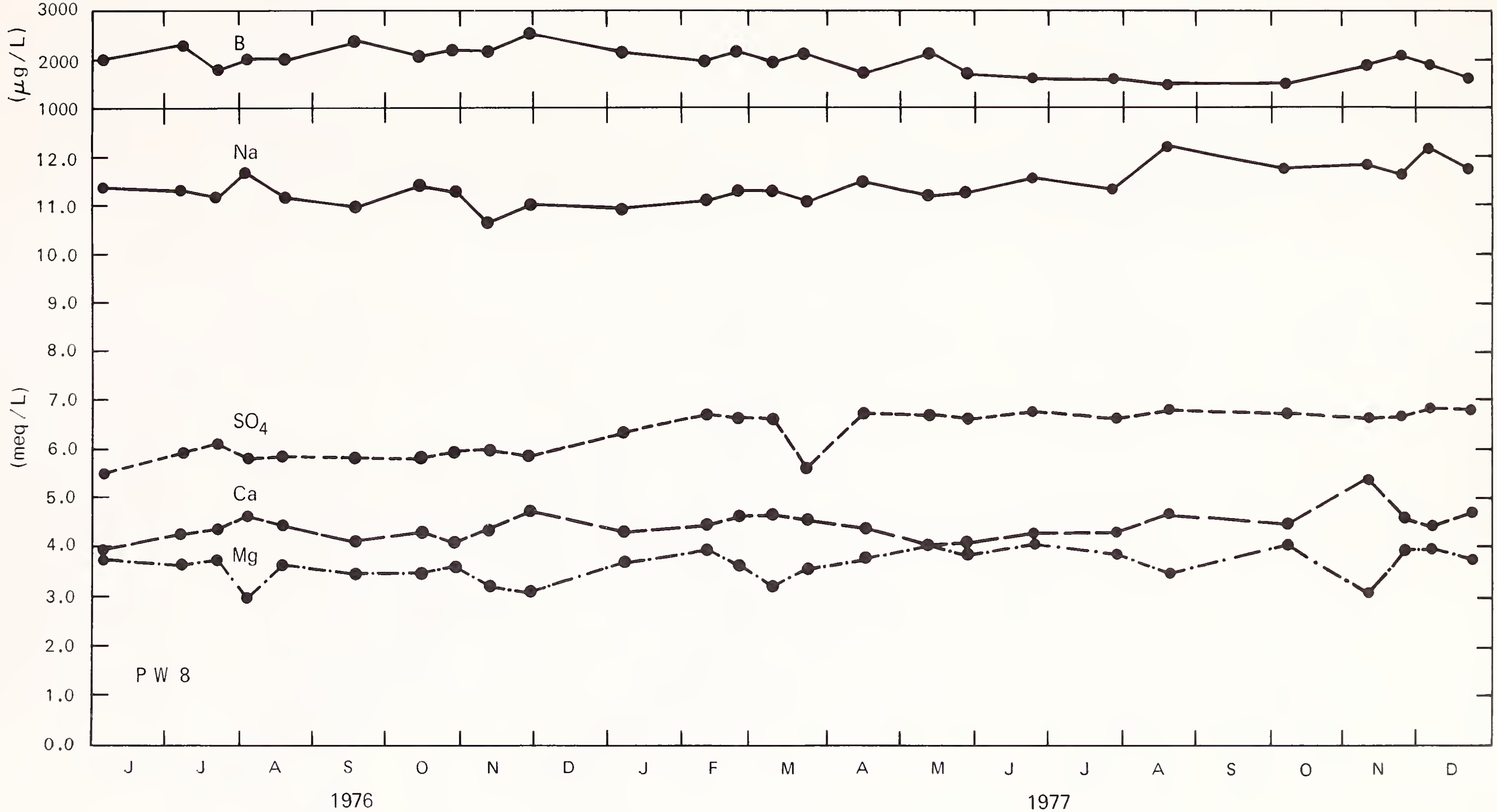
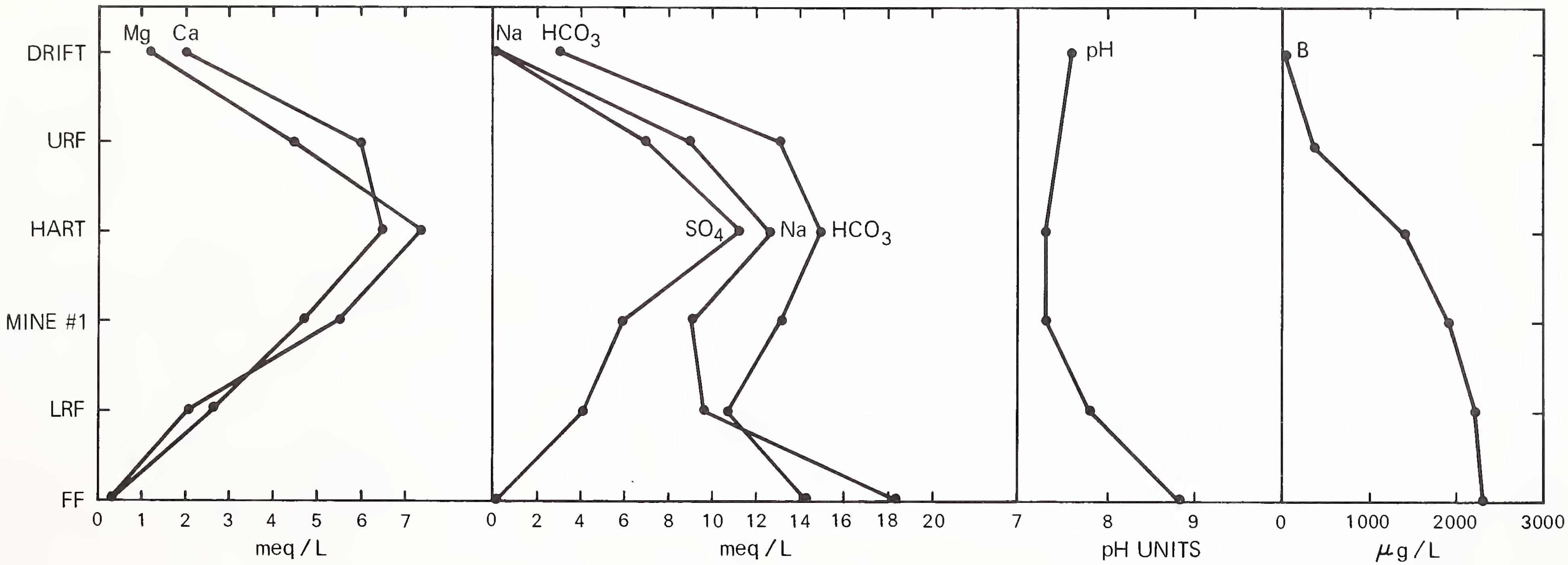


Figure 8.--Diagram showing temporal variations in selected chemical parameters in mine well Number 8.



EXPLANATION

Drift - Glacial drift unconsolidated gravel, sand, clay

URF - Ravenscrag Formation above Hart seam - interbedded sandstones, siltstones, and shales

Hart - Hart coal seam in Ravenscrag Formation

Mine #1 - Mine dewatering well in Hart coal seam

LRF - Ravenscrag Formation below Hart coal seam interbedded sandstones, siltstones, and shales

FF - Frenchman Formation - interbedded sandstones, siltstones, and shales

Figure 9.--Diagram showing generalized vertical variation in concentrations of selected chemical constituents.

sampling of ground water in the area undoubtedly would yield even greater ranges in variability among parameters.

Chemical Quality of Water in Formations

The general chemical quality characteristics of the ground water sampled in the geological formations of the Poplar River Basin are described below.

Sediments Above Ravenscrag Formation

The water in these sediments may have low dissolved solids and be very low in boron. However, where underlying formations drain through these sediments, as for example in stream valleys, the water may be similar to that in the lower formations and be of relatively poor quality from the standpoint of increased salinity and boron.

Ravenscrag Formation Above Hart Coal Seam

The water in this formation generally is high in dissolved solids and is a hard calcium, magnesium, sulfate, bicarbonate type water. There are some indications that boron concentrations are lower in upper Ravenscrag waters than in those from the underlying strata, but there are insufficient data available to make this conclusion with certainty. The one sample collected from this aquifer by the GWQQC had high values for dissolved uranium (190 μg/L), selenium (63 μg/L), and nitrate (63 mg/L as N). The high uranium and selenium values occurring together are suggestive of the presence nearby of a uranium roll-type deposit. These deposits are found throughout areas underlain by lignite deposits. They are generally small and no large commercial deposits have been developed. The high nitrate found in this well (63 mg/L as N) may be due to surface contamination, but surface contamination does not appear to be the source of the uranium and selenium, although the possibility exists. Surface organic pollutants may have caused the uranium and selenium present in the aquifer to go into solution. It is possible that other small deposits of uranium exist in the area to be mined, and may present a problem if excavated and mixed with other overburden. Exposure to oxidizing conditions tends to mobilize uranium and selenium, and they may reach high values in ground waters draining spoil piles.

In stream valleys containing perennial streams, upward ground-water movement from the underlying formations to the Ravenscrag above the Hart seam occurs. This, combined with natural softening processes as the ground water moves from recharge to discharge areas within the formation, results in a soft water with sodium and bicarbonate as the dominant ions.

Hart Coal Seam

Ground water from the Hart coal seam generally is high in dissolved solids (>1,000 μg/L), and is hard because calcium, magnesium, sulfate, and bicarbonate are the dominant ions. The boron concentration generally is between 1,000 and 2,000 μg/L. Iron and manganese are both high in water from this aquifer and may present problems for domestic use. Radium-226 and uranium also are relatively high, although their levels do not exceed established criteria. Because of the similarity of the water from the Hart coal seam and the water in the Ravenscrag above and below the seam, it is difficult to determine if the chemical quality of the water pumped to dewater the seam is or will be affected by the inflow of water from overlying and underlying formations. Results from mathematical model studies described later indicate that over 80 percent of the pumped water is likely to be derived from the adjacent formations. However, because the water in the Ravenscrag Formation above and below the Hart coal seam is chemically similar to Hart coal seam water, it will be difficult to detect any changes in the quality of water discharged by the mine dewatering wells. The effect of Girard Creek leakage on the hydraulic potential, which defines the potentiometric surface, will be almost instantaneous. However, physical transport of water leaking from Girard Creek through the underlying formations to the mine dewatering wells will be extremely slow (less than 10 m/yr). Consequently the effect on the quality of the water discharged from the mine dewatering wells will be undetectable in most instances. Exceptions to this may occur where Girard Creek is adjacent to the mining area or where fractures allow direct connection and rapid transport of water between Girard Creek and the pumping wells. Of course, local anomalies such as the previously described exposure of small uranium deposits to oxidizing ground water could alter the quality of water in the Hart coal seam in the vicinity of dewatering operations.

Ravenscrag Formation below the Hart Coal Seam

The chemical quality in this aquifer ranges from a hard calcium, magnesium sulfate, bicarbonate water similar to the water in the Hart coal seam, to a relatively soft sodium, bicarbonate water similar to the underlying Frenchman Formation.

The chemical quality of water in this aquifer is determined by depth below the surface and position relative to recharge and discharge areas. The harder waters are found in the recharge areas and where the aquifer is close to the surface, while the soft waters occur in discharge areas and where the aquifer is deeply buried.

The boron concentration in water from this aquifer is generally higher than in the overlying aquifers. The sample collected by the GWQQC contained 2,000 μg/L boron. The same water sample contained 26 μg/L phenol, a value well above established criteria for drinking water. Further study of phenol concentrations in this aquifer is needed, to establish their extent and significance.

Frenchman Formation

Water in the Frenchman Formation is generally a sodium-bicarbonate type. It has a distinctive brown color due to unidentified organic material. Most water samples from this aquifer contain over 2,000 μg/L boron. As mentioned

previously, water from this aquifer contains relatively high concentrations of molybdenum. Floride also is above established criteria for human consumption, and could cause mottled teeth. Fluoride levels do not appear to be high enough to cause fluorosis in cattle. The high SAR value (>25) indicates that this water is generally unsuitable for irrigation.

Model of the Geochemical System

Most of the variability in the chemistry of ground water in the study area can be explained by a conceptual geochemical model which is discussed in the following paragraphs. In recharge areas oxygenated water rapidly reacts with the surrounding rock as it infiltrates to the water table. Except in areas of relatively clean glacial outwash, the water contacts relatively unleached reactive minerals including varying amounts of pyrite, - FeS_2. The dissolution reactions probably involve carbonate minerals, pyrite, and clays, and result in a water containing high calcium, magnesium, iron, sulfate, and bicarbonate with a relatively low pH between 6.5 and 7.5. As shown in Table 6 (samples 1G, 2G, 4G, 5G, 6G) the water is close to, or slightly above saturation with respect to the most common carbonates in the area (dolomite $MgCa(CO_3)_2$, calcite $CaCO_3$, and siderite $FeCO_3$). The glacial drift water sample (4G) with the lowest saturation indices with respect to the carbonates probably is from outwash material containing small amounts of pyrite or carbonate minerals. This conclusion is further justified by noting that the dissolved-solids concentration was low (185 mg/L) and the pH relatively high (7.6). Sulfate (14 mg/L) and sodium (1.4 mg/L) had low concentrations.

As the ground water moves through the aquifers towards points of discharge (see Fig. 5) it gradually undergoes a change in chemical composition. The changes include sulfate reduction and ion exchange of calcium, magnesium, and strontium for sodium. The sulfate reduction is caused by sulfate reducing bacteria which use dissolved organic compounds as an energy source. In the absence of additional sulfate from gypsum $-CaSO_4 \cdot 2H_2O$, or anhydrite $-CaSO_4$, bacteria can reduce the sulfate concentrations in ground water from several hundred milligrams per liter to only a few milligrams per liter. The sulfide ions produced by this process generally react with iron and other metals in solution to produce insoluble sulfides. Therefore, such waters are generally low in trace metals.

Ion exchange processes remove the alkaline earth metals--calcium, magnesium, and strontium--from solution and replace them with sodium. Additional solution of carbonates is controlled by increases in pH of the ground water to about 8.5 or 9.0, pH values at which the carbonates are only slightly soluble and at which equilibrium between exchange and carbonate solubility is maintained. As shown by samples 3G and 9G (Table 6), the water in these samples is still close to saturation with respect to the carbonate minerals, even though these samples have very low concentrations of calcium, magnesium, and strontium.

The type of ground water that results from these geochemical processes is best illustrated by samples from the Frenchman Formation. For example, water from the well at the International Border station contained 6 mg/L

calcium, 2.5 mg/L magnesium, 0.15 mg/L strontium, and 10 mg/L sulfate, and had a pH of 8.8. This type of water is not restricted to the Frenchman Formation but, as shown in Figure 5, may occur at depth below recharge areas or near the surface in discharge areas. Water in the Ravenscrag Formation that has traveled long distances and has not mixed with recharge water also will become a sodium-bicarbonate type water.

Comparison of Ground-Water and Surface-Water Chemical Quality Before Mining

During low flow periods the water in the streams throughout the area is supplied by ground water. Therefore, the chemical quality of the stream water during low flow should be similar to that of the ground water. During periods of high flow and surface runoff, the stream chemical quality represents a mixture of surface runoff water and ground-water flow (see Table 7, sample collected on 3/18/76). Thus, on an annual basis, surface-water chemical quality would be expected to vary more than ground-water chemical quality. In addition to variations in stream chemical quality resulting from mixtures of runoff and ground-water flow, aquatic organisms also can have an important influence on stream water quality, especially aquatic organisms capable of carrying out photosynthesis. Among the important influences of photosynthetic organisms on water quality are:

(1) Removal of trace elements from water when required as micronutrients.

(2) Removal of nitrogen and phosphorus from water.

(3) Removal of significant amounts of carbon dioxide from water. This activity results in a reduction of the bicarbonate concentration of the water and raises the pH. The higher pH may result in appreciable precipitation of calcium carbonate.

(4) Removal of silica from the water by diatoms.

Most of the effects of photosynthetic organisms are seasonal, being most pronounced during warm sunny weather. Table 7 shows the difference between summer and winter stream chemical quality. As discussed above, the major effects of photosynthetic organisms can be seen in the differences in pH, calcium, silica, and bicarbonate. The close similarity between ground water and stream water during low-flow periods also is shown in Table 7. Excellent correlation would not be expected between the chemical quality of a stream during low flow and the results of a water sample from a single well because ground water in the area varies considerably and streamflow integrates ground-water discharge from a large area.

Table 6.--Saturation Indices for Water Samples Collected by the GWQQC May 1978
(G, ground water; S, surface water. See Table 3 for sample site location and site description)

Saturation index ($\log \frac{\text{ion activity project}}{\text{equilibrium constant}}$)

No.	Sample (Field temperature °C)	Anhydrite		Aragonite		Calcite		Celestite		Dolomite		Gypsum		Magnesite		Quartz		Siderite		Strontianite	
		Field temperature	+6°C	Field temperature	+6°C	Field temperature	+6°C	Field temperature	+6°C	Field temperature	+6°C	Field temperature	+6°C	Field temperature	+6°C	Field temperature	+6°C	Field temperature	+6°C	Field temperature	+6°C
1G	Mine Dewatering Well PW 1 Hart Coal Seam (7°C)	-1.3	-1.3	0.0	0.1	0.2	0.3	-2.1	-2.1	0.4	0.7	-0.9	-1.0	-0.1	0.1	0.7	0.6	0.4	0.5	1.1	1.2
2G	Mine Dewatering Well PW 11 Hart Coal Seam (7°C)	-1.3	-1.3	-.1	.0	.1	.2	-2.1	-2.1	.3	.5	-.9	-1.0	-.2	.0	.7	.6	.3	.4	1.1	1.1
3G	Domestic Well Frenchman Formation (9.5°C)	-3.0	-2.9	.1	.2	.4	.5	-3.4	-3.4	.4	.6	-2.6	-2.6	-.3	-.2	.5	.4	1.3	1.4	1.7	1.7
4G	Domestic Well Surficial Drift (4.5°C)	-2.7	-2.7	-.6	-.5	-.3	-.2	-4.3	-4.3	-1.0	-.7	-2.3	-2.3	-1.0	-.8	.5	.4	-1.2	-1.0	-.1	-.1
5G	Domestic Well Hart Coal Seam (2.1°C)	-1.1	-1.0	.0	.1	.2	.3	-1.8	-1.8	.4	.7	-.6	-.6	-.1	.0	.8	.7	.8	.9	1.2	1.3
6G	Domestic Well Ravenscrag above Hart Seam (5°C)	-.3	-.3	.2	.3	.4	.6	-1.5	-1.5	1.0	1.3	.1	.1	.2	.4	.7	.6	-.9	-.8	1.0	1.1
7G	Domestic Well Ravenscrag Below Hart Seam (8.5°C)	-1.6	-1.6	.2	.3	.4	.5	-2.2	-2.1	.7	1.0	-1.3	-1.3	.0	.1	.5	.4	1.4	1.6	1.6	1.7
8G	Mine Dewatering Well PW 11 Duplicate of No. 2 (7°C)	-1.3	-1.3	-.1	.0	.1	.2	-2.1	-2.1	.3	.6	-.9	-1.0	-.2	.0	.7	.6	.3	.4	1.1	1.1
9G	Canada Customs Station Well Frenchman Formation (10.6°C)	-3.8	-3.8	.4	.5	.6	.7	-4.3	-4.2	1.1	1.3	-3.5	-3.5	.1	.3	.6	.5	1.2	1.4	1.9	1.9
10G	Domestic Well (9°C)	-1.4	-1.3	.2	.3	.4	-5.4	-2.0	-2.0	.7	1.0	-1.0	-1.0	.0	.1	.4	.3	1.2	1.3	1.5	1.5
11S	Poplar River (14.1°C)	-1.7	-1.7	1.2	1.2	1.4	1.5	-2.4	-2.4	3.0	3.2	-1.4	-1.4	1.3	1.4	.4	.3	1.4	1.6	2.4	2.4
12S	East Poplar River International Border (14.9°C)	-1.4	-1.3	1.2	1.3	1.5	1.6	-1.9	-1.8	3.2	3.4	-1.0	-1.0	1.4	1.5	.4	.3	2.6	2.7	2.6	2.6
13S	Seep Below Morrison Dam (7.1°C)	-1.4	-1.3	.0	.1	.2	.4	-1.9	-1.9	.5	.8	-1.0	-1.0	-.1	.0	.7	.6	-1.0	-.9	1.4	1.5
14S	Reservoir Water at Morrison Dam (11.7°C)	-1.8	-1.8	.8	.9	1.1	1.2	-2.6	-2.6	2.4	2.6	-1.4	-1.5	1.0	1.1	.0	-.1	1.0	1.1	2.0	2.0
15S	Morrison Reservoir Headwaters (14.5°C)	-2.0	-2.0	.6	.7	.8	.9	-2.9	-2.9	1.7	2.0	-1.7	-1.7	.6	.7	.2	.1	.6	.8	1.6	1.6
16S	East Poplar River Upstream of Reservoir (14.6°C)	-1.8	-1.7	1.0	1.1	1.3	1.4	-2.6	-2.6	2.7	2.9	-1.4	-1.5	1.0	1.2	.1	.0	1.3	1.5	2.1	2.2
17S	Coronach Reservoir (12.4°C)	-1.8	-1.7	1.0	1.1	1.2	1.3	-2.5	-2.5	2.6	2.9	-1.4	-1.4	1.1	1.2	-.8	-.9	.9	1.0	2.2	2.2
18S	Fife Lake (11.4°C)	-1.9	-1.9	.9	1.0	1.2	1.3	-2.3	-2.3	3.4	3.6	-1.6	-1.6	1.9	2.0	-.2	-.4	1.8	1.9	2.6	2.6
19S	Girard Creek Above Mine discharge (12.9°C)	-1.2	-1.1	.8	.9	1.0	1.1	-2.2	-2.2	2.3	2.5	-.8	-.8	.9	1.0	.2	.1	.6	.8	1.7	1.7
20G	Frenchman Formation Duplicate of No. 9 (10.6°C)	-3.9	-3.9	.3	.4	.6	.7	-4.3	-4.3	1.1	1.3	-3.5	-3.6	.2	.3	.6	.4	1.2	1.3	1.9	1.9
21S	Fife Lake, Duplicate of No. 18 (11.4°C)	-1.9	-1.9	.9	1.0	1.2	1.3	-2.3	-2.3	3.4	3.6	-1.6	-1.6	1.9	2.0	-.2	-.4	1.8	1.9	2.6	2.6
22S	Girard Creek Below Mine Water Discharge (10.9°C)	-1.3	-1.3	.8	.9	1.0	1.1	-2.0	-2.0	2.2	2.4	-1.0	-1.0	.8	1.0	.4	.3	.7	.8	2.0	2.0

Table 7.--Seasonal Variation in Selected Water Quality Parameters for East Poplar River at International Boundary, and for Mine Discharge Well Number 1

	Surface water			Ground water
Date	3/18/76	7/17/75	12/19/75	5/9/78
Discharge (m^3/s)--	1.5	1.2	0.008	N/A
pH----------------	7.9	9.1	7.6	7.3
Dissolved Solids (mg/L)	97	1,480	1,180	1,070
Calcium (mg/L)----	12	28	81	95
Magnesium (mg/L)--	4.8	63	51	67
Sodium (mg/L)-----	12	390	280	210
Bicarbonate (mg/L)	73	717	929	800
Sulfate (mg/L)----	20	500	270	290
Silica (mg/L)-----	3.3	0.9	21	15
Boron (μg/L)------	120	3,100	2,300	1,900

Boron seems to behave as a conservative chemical constituent both in surface and ground water. Some water samples collected from the East Poplar River at the International Border had higher boron values (3,100 μg/L) than any samples collected from ground water. This may merely reflect inadequate ground-water sampling or it may be a result of relatively high boron water released to Girard Creek from bank storage; water which was originally from Fife Lake overflow.

Expected Impact of SPC Plant on Hydrogeologic System

Mathematical Models

The hydrogeologic system of the upper Poplar River Basin is so complex that response to changes in recharge and discharge cannot be predicted using normal analytical techniques or reasonable judgement. Therefore, mathematical models were used to simulate the hydrogeologic system. Mathematical models integrate the combined effects of recharge, discharge, and hydrogeologic boundaries in a manner that cannot be achieved using any other technique. Two models were used to probe the behavior of the hydrogeologic system and to predict responses to future plant operations.

The first model was a finite-element model prepared for the coal aquifer, layer 3, and used to estimate the combined effects of dewatering and expected leakage from adjacent aquifers into the coal aquifer as a worst case condition. The area represented by this model is roughly equivalent to the area occupied by the basin of the East Poplar River and includes all parts of the Poplar River Basin in which significant ground-water quantity and quality effects may reasonably be expected. The finite-element model requires that a map of the aquifer be discretized or subdivided into triangular subregions called elements as shown in Plate 6. The corners of the elements are referred to as nodes. The input data are specified at these nodes for which the model then calculates changes in ground-water levels.

The model used here simulates the flow of ground water within the coal layer, assumed to be bounded at the top and bottom by impervious formations. The coal aquifer has been assigned areal variations in transmissivity based on field data (see Table 5). The ground-water flow is described by the following differential equation for which the finite-element technique provides a solution at the nodes of the triangles:

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right) + q_1 - Q = S\frac{\partial h}{\partial t} \qquad (1)$$

where

h = hydraulic head, or piezometric head (ground-water level)
T = transmissivity of aquifer
q_1 = known flux, into or out of the aquifer
Q = pumping rate at specified nodes (source or sink function)
S = storage coefficient of aquifer
x,y = areal coordinates

For further information on the subject, the reader is referred to the principles developed by Zienkiewicz (1971), Wachspress (1975) and Pinder and Frind (1972).

The following assumptions were made in simulating the behavior of the coal aquifer.

1. The peripheral boundary nodes and Cookson Reservoir were simulated as constant-head nodes where no changes in water levels may occur.
2. The current extraction from wells located in T 2, R 26, and 27 is 14,800 m^3/d. Pumping was divided equally between nodes 48 and 49 as shown in Plate 6.
3. The areal extent of the coal aquifer is as shown in Plate 3. Hydraulic continuity is maintained across the stream valleys by deposits of the Empress Group or glacial fill. Values of the transmissivity were obtained using the data in Table 5.
4. The streams are not hydraulically connected to the coal aquifer.

The finite element model was used to simulate the effect of pumping at the specified rates at steady state conditions. The steady-state analysis assumes that (1) flow below and above the aquifer is essentially vertical, (2) an impermeable boundary (Bearpaw Formation) below the coal aquifer precludes the possibility of underlying source beds, and (3) water pumped must equal the recharge rate from above. Simulated rates of recharge were related to average annual precipitation in the Poplar River Basin. The first simulation presumed a steady uniform recharge of 1 percent of average annual precipitation, or 3.5 mm/yr (millimeters per year); results are shown in Plate 7. Predicted change in the potentiometric surface of the coal aquifer ranges from less than 0.1 m near the International Border to about 15 m near the dewatering wells. Growth of the drawdown cone was reduced in T 1, R 26 W2 because of local leakage from Cookson Reservoir into the coal aquifer. The drawdown cone affects the aquifer over 12 townships.

The second simulation presumed a steady uniform recharge of 6 percent of average annual precipitation, or 21.5 mm/yr. General experience and simulation with similar models suggest that 5 to 6 percent of annual precipitation best represents normal recharge in southern Saskatchewan. Results of the second simulation are shown in Plate 8. Predicted change in the potentiometric surface of the coal aquifer ranges from zero near the International Border to about 8 m near the dewatering wells. The drawdown cone has spread mostly to the north and west because of local leakage from Cookson Reservoir. The areal extent of the drawdown cone has been reduced about 50 percent because of the additional recharge. The finite-element model thus indicated that the decline of water levels for the coal aquifer will probably be minor in Montana.

A second and more detailed transient mathematical simulation model was prepared to represent a part of the upper Poplar River Basin similar to that area covered by the finite-element model. The required model had to simulate the interrelationships between adjacent aquifers of different hydrologic characteristics and interconnected streams. The model selected was a finite-difference model capable of simulating three dimensional flow (Trescott, 1975; Trescott and Larson, 1976). The model uses a variable grid of block-centered nodes in a layered structure. The aquifer systems simulated may be heterogeneous and anisotropic and may have irregular boundaries. The model uses the strongly implicit procedure to solve the following equation:

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right) + b\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) = S'\frac{\partial h}{\partial t} + bW(x,y,z,t) \qquad (2)$$

where

h = hydraulic head, or piezometric head (ground-water level)
T_{xx} = principal component of transmissivity tensor in x direction
T_{yy} = principal component of transmissivity tensor in y direction
K_{zz} = principal component of hydraulic conductivity tensor in vertical direction
$W(x,y,z,t)$ = volumetric flux per unit volume
S = storage coefficient
x,y,z = space coordinates
b = layer thickness

The solution of equation (2) requires that the principal coordinate axes of the grid be aligned with the principal directions of the transmissivity. Tectonic activity is probably the principal directional influence on transmissivity. Principal tectonic fracture directions are N 45° W and N 45° E (Stone, 1974) for formations of post-Laramide age (Hart coal seam and younger rocks). Therefore the model grid was designed so that the x and y directions were aligned along these trends, as shown in Plate 9. Column- and row-spacing widths range from 1.0 to 5.0 km (kilometers). The model grid covers a total area of 70 km by 38 km, or 2,660 km^2. Five layers were incorporated in the vertical grid as designated in Table 4 and with hydrologic characteristics shown in Table 5. The model includes all aquifers above the Bearpaw Formation and accounts for the hydrologic effects of Cookson Reservoir, Fife Lake, Poplar River, Goose Creek, Girard Creek, East Poplar River, and Cow Creek as constant head nodes. The model assigns zero transmissivity values to all peripheral nodes for all layers.

The model simulations required certain assumptions. Initially the potentiometric surfaces of all five layers were presumed flat and equal except for the surface at Cookson Reservoir in layer 5. Therefore: (1) the predicted declines or rises in the potentiometric surfaces and stream gains or losses are predicted <u>changes</u> that will occur, and (2) natural recharge and discharge are assumed constant in the simulation

period. Inherent errors in the model include the assumption that the hydrologic characteristics of aquifers do not vary with changes in the head. Actually hydraulic conductivity, transmissivity, specific yield, and the storage coefficient all may vary with changes in head, thus the model only gives approximate results.

Model calibration was effected by simulating changes in ground-water recharge and discharge and comparing measured and simulated changes in the potentiometric surfaces of aquifers. A schematic diagram showing effects of a pumping well on the flow system is shown in Figure 10. Twelve production wells completed in the Hart coal seam were pumped in 1976-78 in order to dewater the coal and overburden material in the southwestern part of T 2, R 27 W2 in Saskatchewan. Locations of wells are shown in Figure 11 and mean discharges of wells are shown in Table 8. The discharge has caused measurable declines in the potentiometric surfaces of the Hart coal aquifer and the upper Ravenscrag aquifer. Leakage from Cookson Reservoir has caused measurable rises in the potentiometric surfaces of the Hart coal and overlying aquifers.

Table 8.--Mean discharge of production wells, spring 1976 to fall 1977, upper Poplar River Basin, Saskatchewan

Well number (see Fig. 11)	Mean discharge (m^3/d)
1	2,300
2	1,100
4	20*
5	420
6	520
8	1,700
10A	1,700
11	960
12A	590
13	2,100
14	1,200
15	30*
Total (rounded)	12,600

* Pumped April-July, 1977 only.

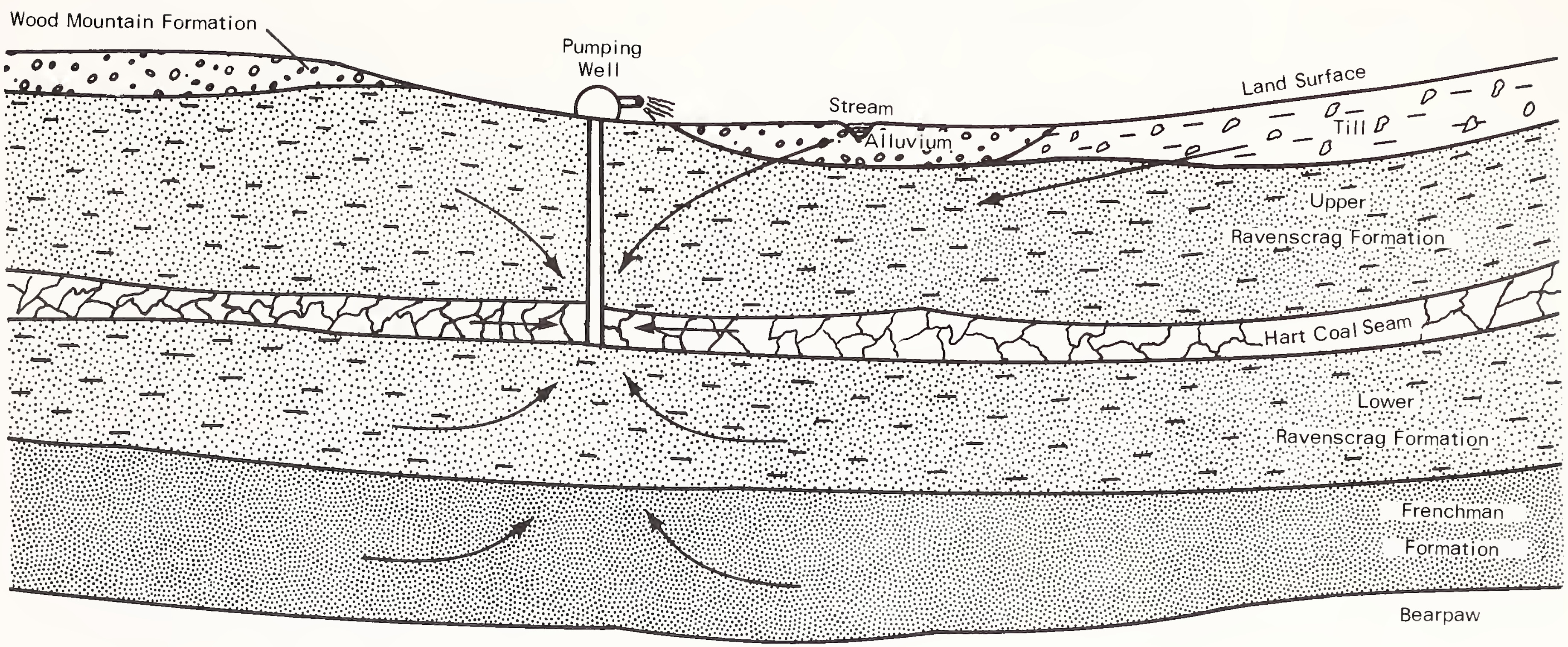


Figure 10.--Schematic diagram showing changes in flow system caused by a pumping well.

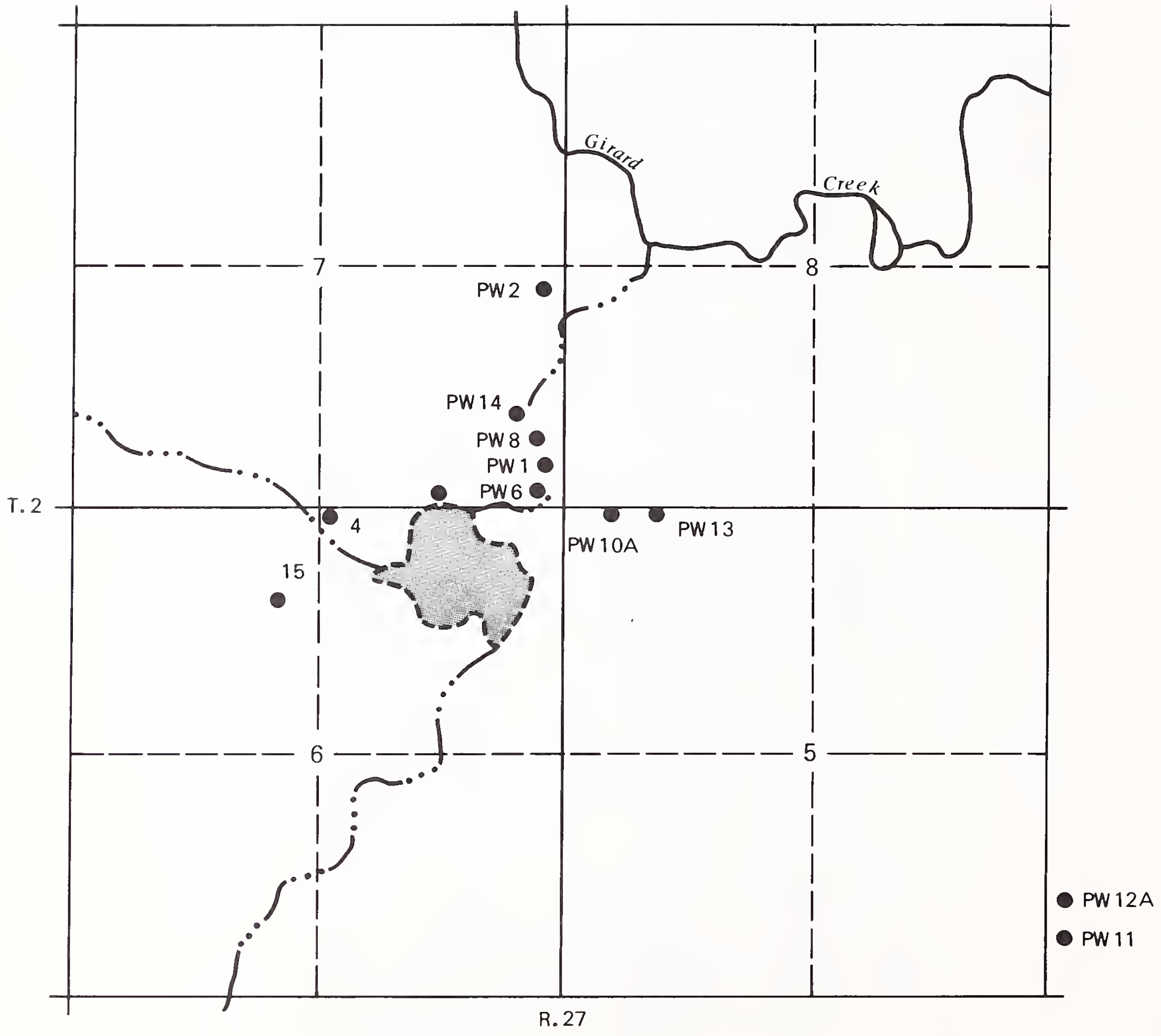


Figure 11.--Location of production wells completed in Hart coal aquifer, 1976-78, upper Poplar River Basin, Saskatchewan.

The leakage rate from Cookson Reservoir was calculated by the mathematical model. During the calibration period the reservoir level was an average of 7 m above the initial general potentiometric surface assumed for all layers. Therefore, the potentiometric surface of level 5 near the reservoir was elevated and maintained as a series of constant-head nodes at a level of 7 m above the general potentiometric surface. The calculated leakage rate from the reservoir ranged from 2,200 to 2,800 m^3/d. Available hydrologic budgets for the reservoir were not sufficiently accurate to permit calculation of a field leakage rate for comparison.

The discharging wells and reservoir leakage were simulated for 435 days. Measured changes are shown in Figure 12 and simulated changes are shown in Figure 13. Reasonable agreement was obtained except possibly in the northern part of T 2, R 27 W2 where control points for measured changes are absent. In order to obtain the elongated drawdown cone in the northwest-southeast direction the transmissivity of layer 3, the Hart coal aquifer, was reduced by 50 percent in the northeast-southwest direction. Apparently fractures trending N 45° W can be assumed to be more open compared to fractures trending N 45° E.

Pumping of wells completed in the Hart coal aquifer also has dewatered the overlying aquifers as shown in Figure 14. A group of observation wells was drilled at different depths in an area about 2.5 km from the dewatering wells. The deepest well was completed in the Hart coal aquifer and the four shallower wells were completed in the upper Ravenscrag aquifer. The hydrographs in Figure 14 show that drawdown of the potentiometric surface increases with depth below land surface down to the Hart seam and a vertical gradient downward has developed in the upper Ravenscrag. Figure 15 shows hydrographs of several groups of observation wells on May 31, 1978. Two groups show a linear gradient has developed and suggest that the upper Ravenscrag has behaved as an aquifer rather than as a confining layer. The other group of wells shows a nonlinear gradient and indicates the effect of included beds of low permeability that retard drainage. The nonlinear group is located close to one of the linear groups and indicates the variety of dewatering behavior that may be expected from the heterogeneous upper Ravenscrag aquifer.

The model was used to analyze the effects of future dewatering and continued leakage from Cookson Reservoir. A proposed mining plan obtained from the plant, Mine, and Reservoir Operations Committee (of the IPRWQB) subdivides the area to be strip mined into 13 blocks (Fig. 16). Physical and mining schedule details for the blocks are listed in Table 9. According to the schedule, Block 1 is to be mined during the first 5-year period (1979-1983); the remaining twelve blocks will be mined successively in pairs over succeeding 5-year periods. The total projected length of the mining operation is thus 35 years, ending in the year 2013.

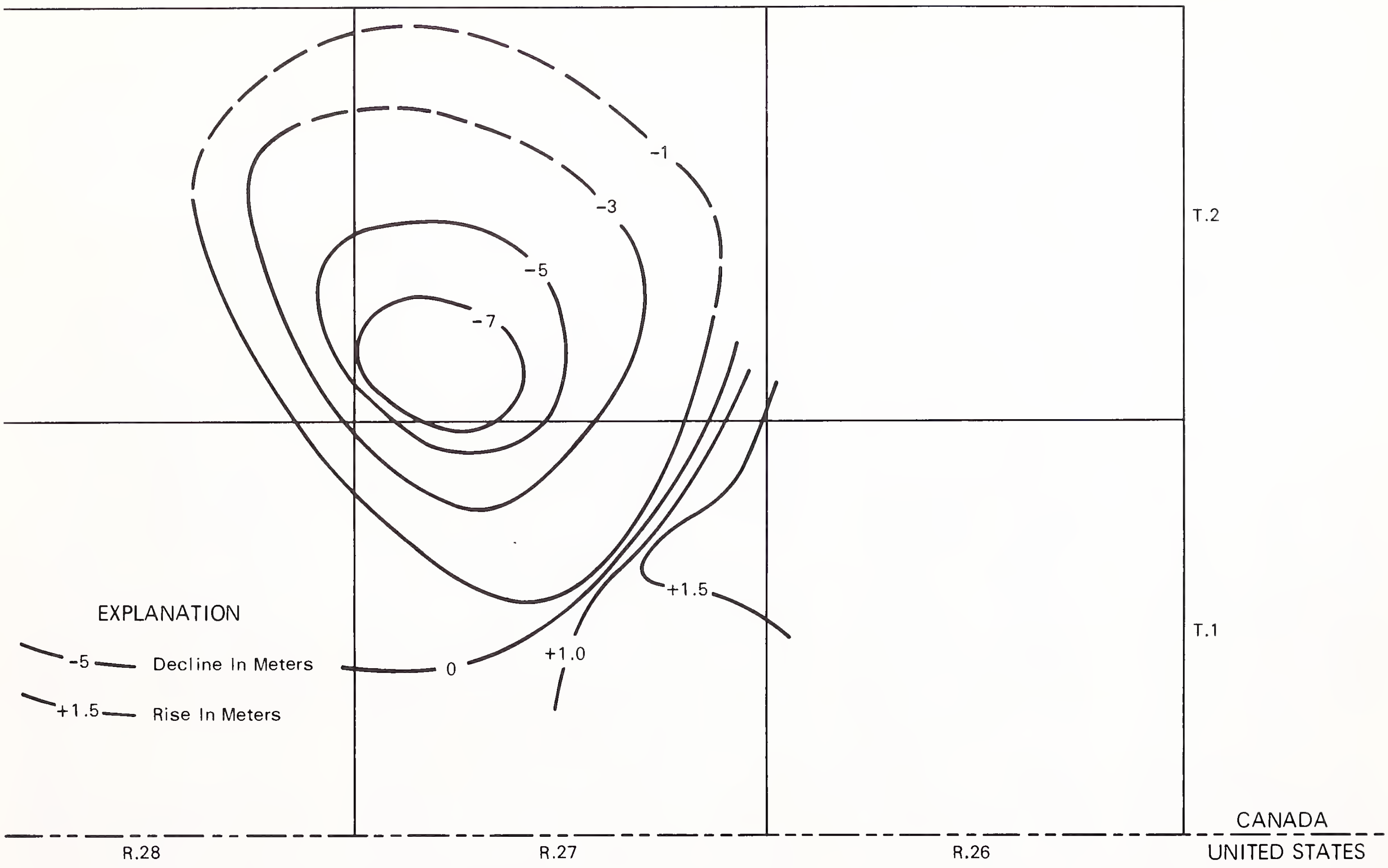


Figure 12.--Measured changes in potentiometric surface of Hart coal aquifer, spring 1976 to fall 1977.

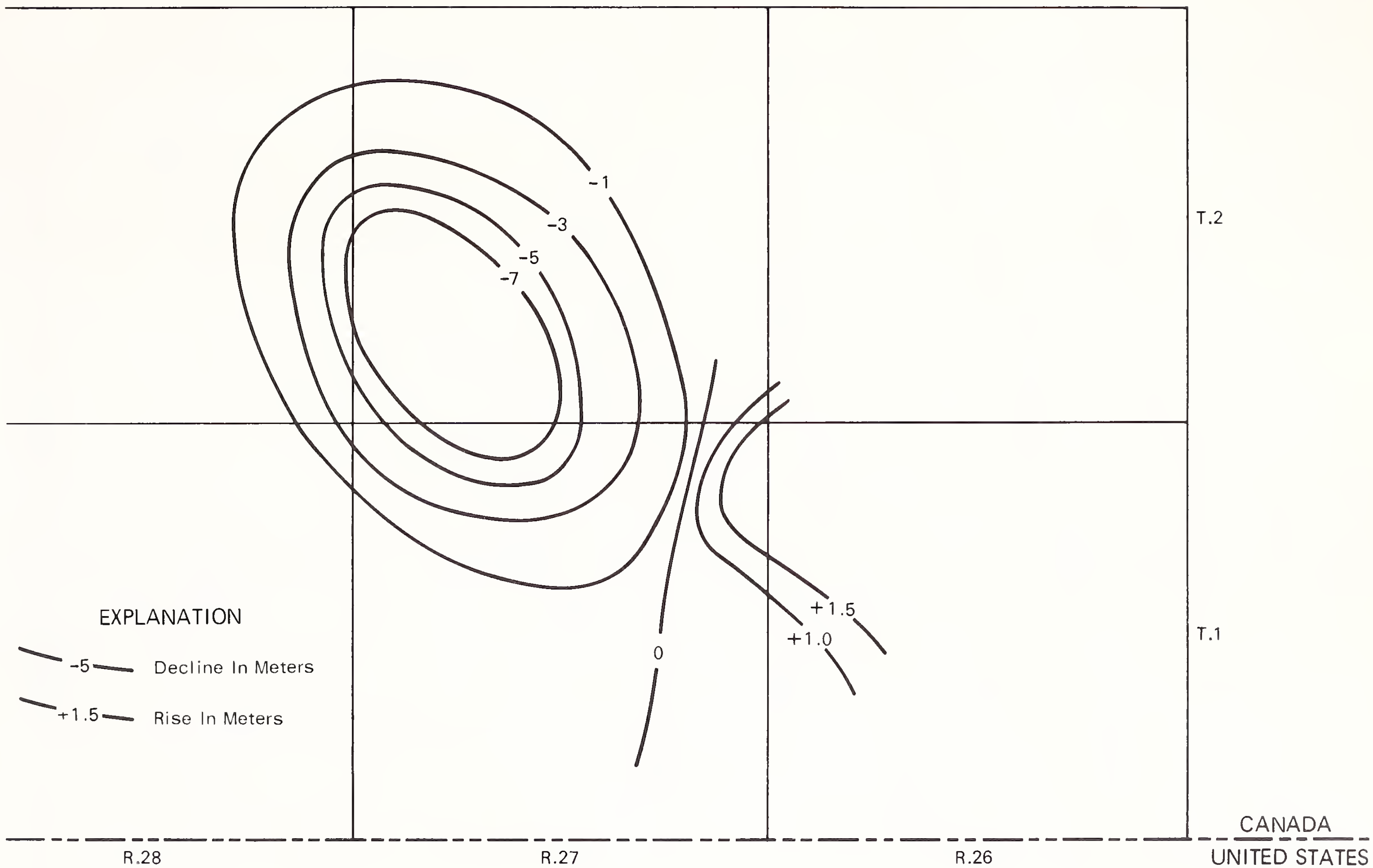


Figure 13.--Simulated changes in potentiometric surface of Hart coal aquifer, spring 1976 to fall 1977.

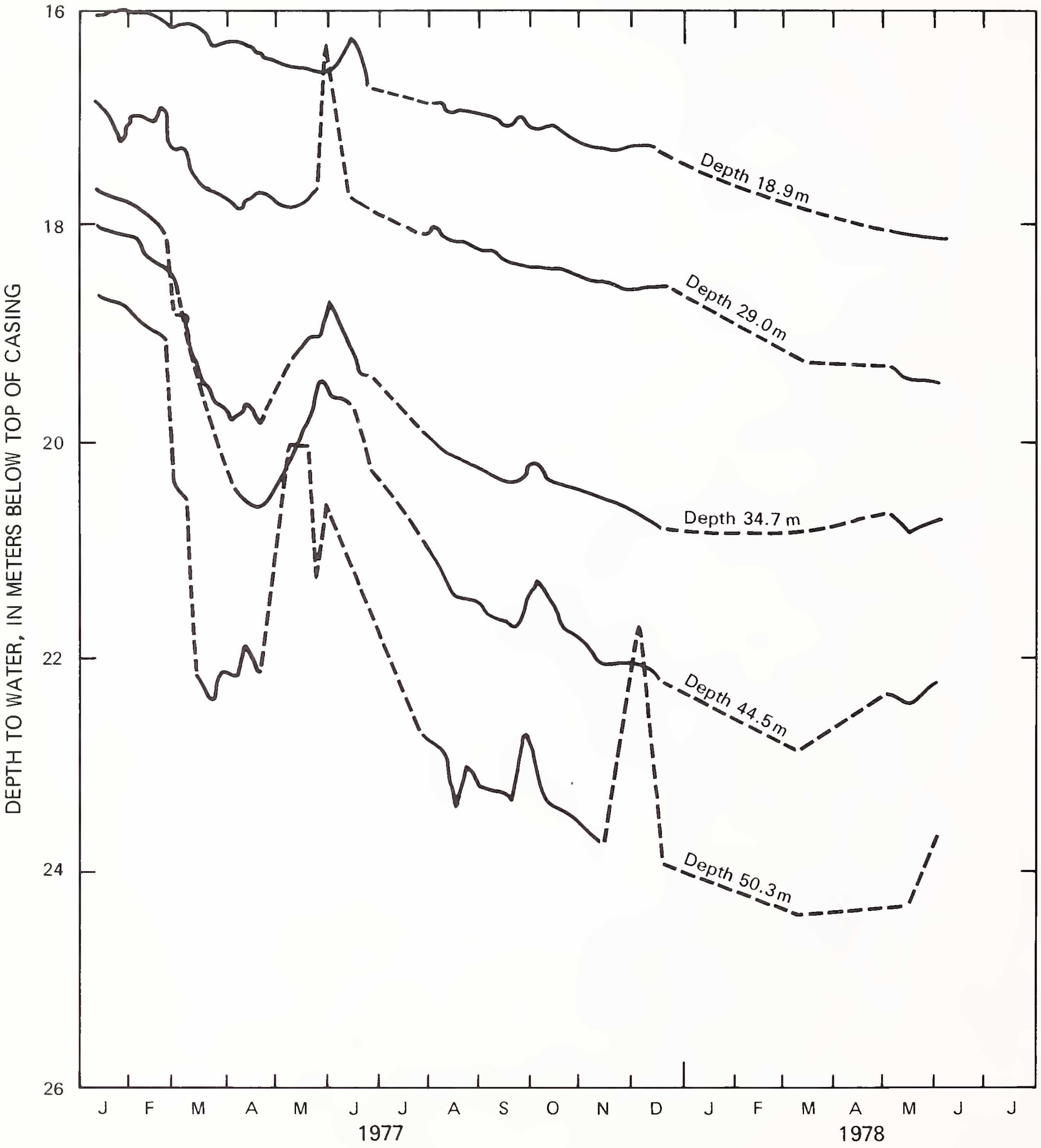


Figure 14.--Hydrographs of observation wells near SW4-2-27-W2.

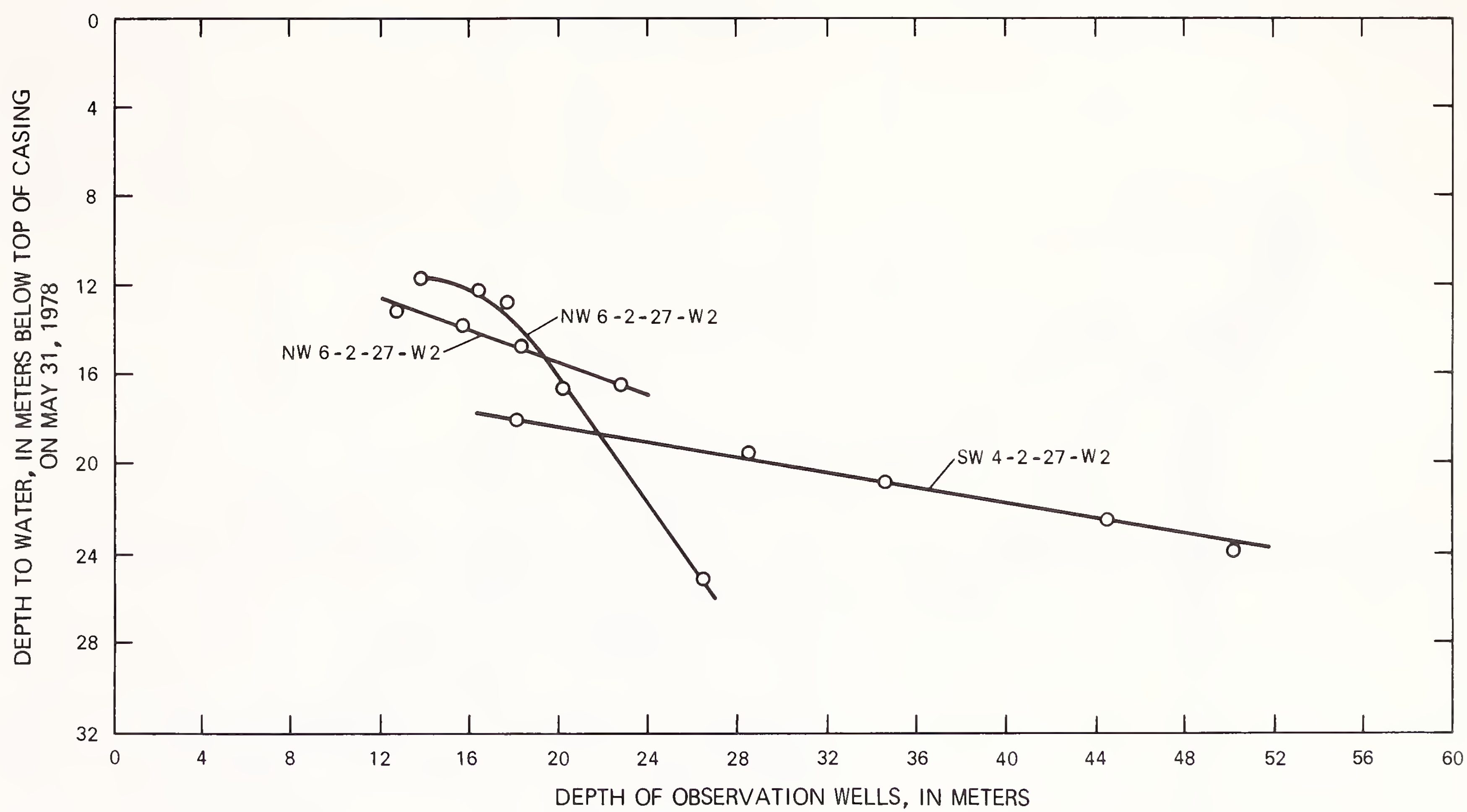


Figure 15.--Hydrographs of observation wells showing linear and nonlinear vertical head distribution in upper Ravenscrag and Hart coal aquifers.

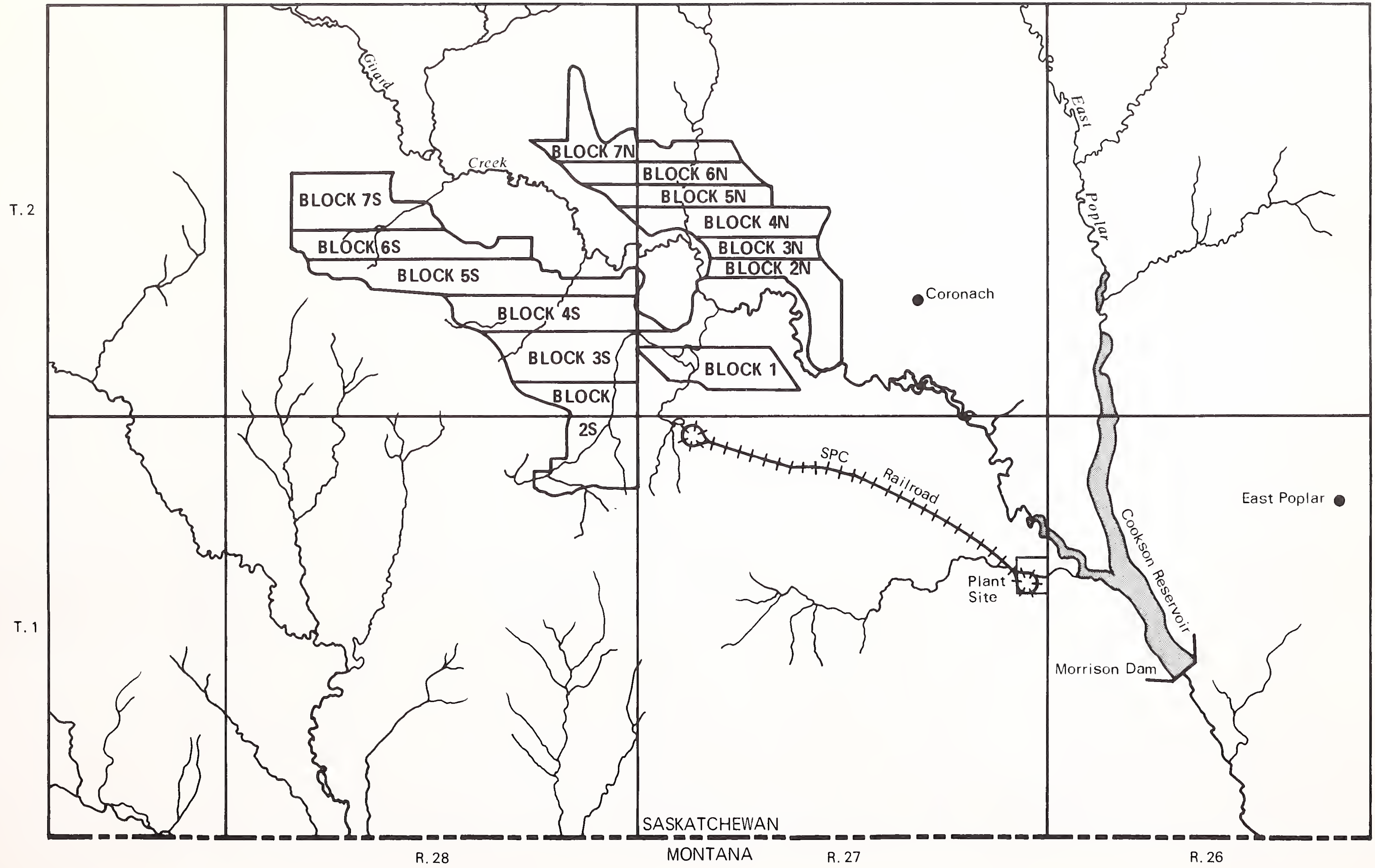


Figure 16.--Proposed mining areas for SPC Power Plant for 1979-2013.

Table 9.--Proposed long-term mining plan 1979-2013 for Hart coal seam, upper Poplar River Basin, Saskatchewan

Block	Surface area (km^2)	Overburden thickness (m)	Approximate mining period
1	2.49	17	1979 - 1983
2N	2.67	31	1984 - 1988
2S	4.57	30	1984 - 1988
3N	1.84	32	1989 - 1993
3S	4.25	27	1989 - 1993
4N	2.56	36	1994 - 1998
4S	4.32	25	1994 - 1998
5N	2.42	34	1999 - 2003
5S	4.12	22	1999 - 2003
6N	2.57	31	2004 - 2008
6S	3.72	30	2004 - 2008
7N	3.01	34	2009 - 2013
7S	3.29	30	2009 - 2013

For the purposes of the finite-difference modeling, it was assumed that the dewatering wells would operate at a steady rate throughout each of the 5-year periods. However, the rates were varied from period to period and from block to block in order to insure adequate drawdowns in the blocks being mined. Table 10 shows the local saturated thickness of the upper Ravenscrag aquifer and the drawdown by the model for the indicated pumping rates. Predicted drawdown is approximately equal to saturated thickness at the indicated pumping rates, so presumably mining can proceed with dewatered overburden.

The following assumptions were made for the finite-difference model simulation concerning future hydrogeologic effects of mining:

(1) The hydrogeologic characteristics of the five layers are the values shown in Table 5, except that the transmissivity of layer 3 was reduced by 50 percent along the N 45° E direction. This horizontal anisotropy is related to the tectonic history of the region.

(2) The hydrogeologic characteristics of the five layers do not vary with time because of changes in head in any layer, even though the expected head changes probably will affect certain characteristics. The errors associated with this assumption are however, probably small.

(3) The hydrogeologic characteristics of the five layers will not vary because of the mining process, even though parts of certain layers will be mined and either consumed (layer 3) or backfilled (layers 4 and 5). Studies by Van Voast and others (1976) indicate that backfilling of mined materials may not

severely change the hydrogeologic properties of the material when compared to the properties prior to mining.

(4) All potentiometric surfaces were assumed to be initially flat and equal in altitude. Natural recharge and discharge were presumed constant and therefore not simulated. The predicted effects are hydrogeologic changes in the systems.

(5) The mining plan listed in Table 9 will be followed and wells for dewatering the overburden will be pumped at the rates shown in Table 10.

(6) Cookson Reservoir will be maintained at a level of 7 m above the initial potentiometric surfaces, and will continue at this level during and after the active mining period from 1979 through 2013.

Table 10.--Required pumping of Hart coal aquifer to produce local dewatering of upper Ravenscrag aquifer

Block	Local saturated thickness (m) of upper Ravenscrag aquifer	Predicted local drawdown (m) in upper Ravenscrag aquifer due to pumping of Hart coal aquifer	Required pumping (m^3/d) of Hart coal aquifer to produce predicted local drawdown in upper Ravenscrag aquifer
1	3.0	3.1	1,500
2N	6.1	6.8	5,400
2S	6.1	8.0	2,600
3N	4.6	4.7	2,500
3S	3.0	4.0	1,100
4N	10.1	10.0	6,000
4S	4.6	6.1	1,600
5N	19.8	19.9	11,500
5S	13.7	13.8	5,500
6N	22.9	21.2	7,800
6S	19.8	19.8	6,000
7N	29.0	27.6	10,200
7S	22.9	22.1	6,200

The model simulated the effects of seven 5-year periods of pumping, followed by three periods of recovery for 10, 10, and 20 years. Therefore, the duration of the simulation period totals 75 years. The predicted pumping and depletion of ground-water and surface-water sources is shown in Figure 17. Surface-water and ground-water depletion declined after the pumping periods. Reservior leakage is only slightly affected by pumping. Details of surface-water depletion are shown in Figures 18 and 19.

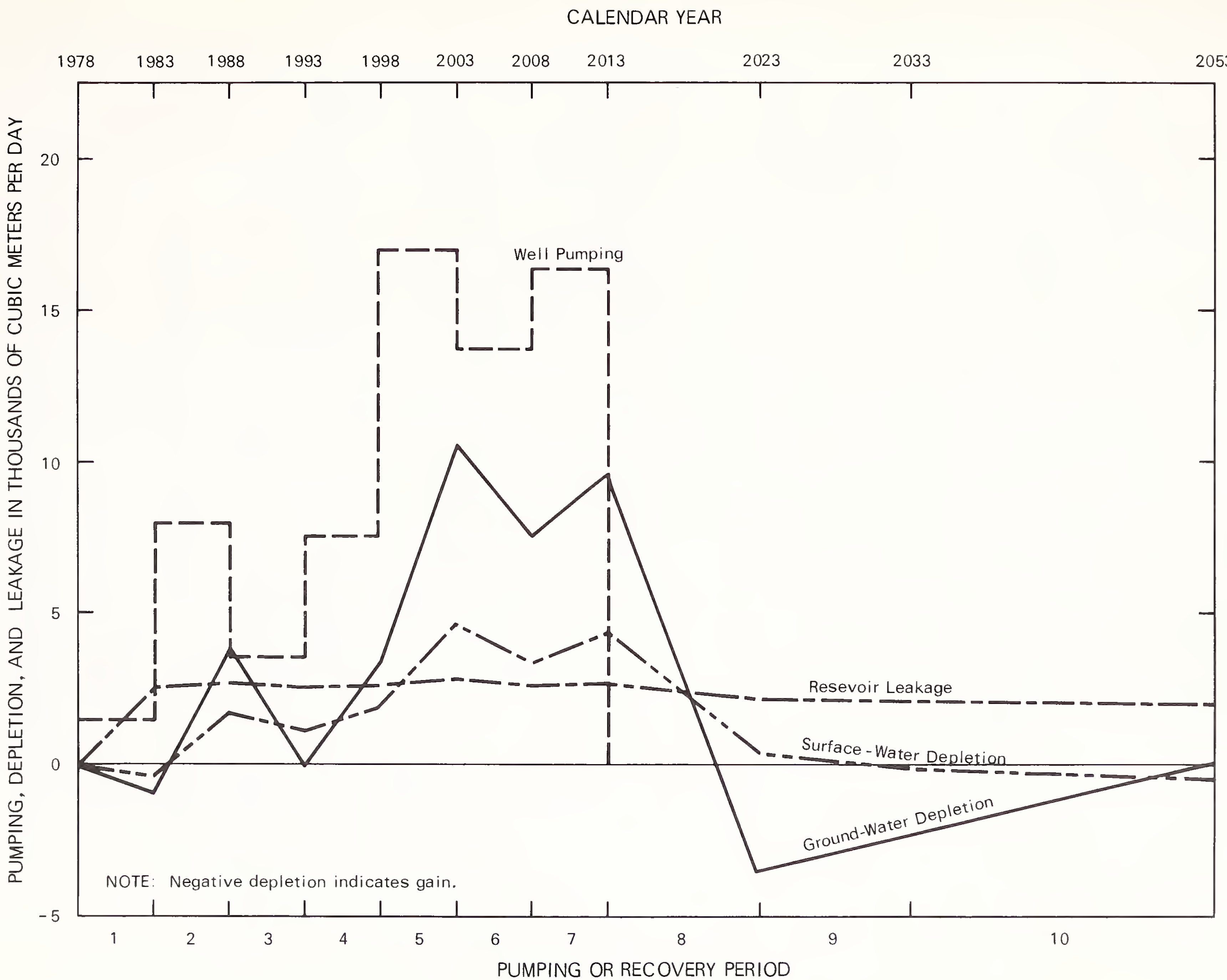


Figure 17.--Predicted pumping, depletion, and leakage, upper Poplar River basin, Saskatchewan and Montana.

Greatest depletion of streams is for Girard Creek during the highest pumping periods, 5 and 7. Girard Creek is located close to the pumping wells and therefore is subject to the greatest depletion. Depletion of Cookson Reservoir is related to required inflow to the reservoir to maintain the level at 7 m above the original potentiometric surfaces. Continued surface-water depletion shown in Figure 17 is mostly due to Cookson Reservoir. The East Poplar River initially shows gains in flow from Cookson Reservoir rather than depletion. However, dewatering depletes the East Poplar River above Cookson Reservoir during pumping periods 4 through 7 as shown in Figure 18. Curves in Figure 19 show a continual gain in Cow Creek due to Cookson Reservoir and smaller depletions of Goose Creek, Poplar River, and Fife Lake. Figures 18 and 19 show that stream depletion will diminish after well withdrawals cease. Streams that gain due to leakage from Cookson Reservoir will continue to gain as leakage from the reservoir continues.

The maximum effect on ground-water storage will occur at the end of pumping period 7 as shown in Figure 17. Predicted change maps for all layers also indicate that the maximum decline in potentiometric surfaces also will occur at this time in the year 2013. Declines and rises in layer 5 occur mostly in the till rather than in the valley-fill alluvium that is recharged by streams. Predicted effects on the Wood Mountain and Flaxville aquifers are negligible.

Predicted effects on layer 4 are particularly interesting because many wells in Montana are completed in this layer. Changes in the potentiometric surface of layer 4 are predicted as shown in Plate 10. The drawdown area extends from Fife Lake to northern Montana. However, the maximum drawdown predicted for Montana is 0.7 m near the border in the north-central part of T 37 N R 46 E. Predicted maximum rise in Montana after 75 years of leakage from Cookson Reservoir is about 0.1 m near the area where the East Poplar River crosses the border. For layers 3, 2, and 1, the pattern of declines and rises are similar to those for layer 4, except that the effects of streams, Cookson Reservoir and Fife Lake are subtle because of the depth of the layers beneath the surface-water sources.

Declining potentiometric surfaces will begin to recover after pumping period 7, so that the lowering of water levels will gradually reduce with time. At the end of period 10 (the third and last simulated recovery period) in the year 2053, the maximum predicted residual declines in potentiometric surfaces will occur in T 2, R 28 W2 in Saskatchewan and are as follows:

Layer	Maximum residual decline (m)
5	4.1
4	2.2
3	2.1
2	1.5
1	1.1

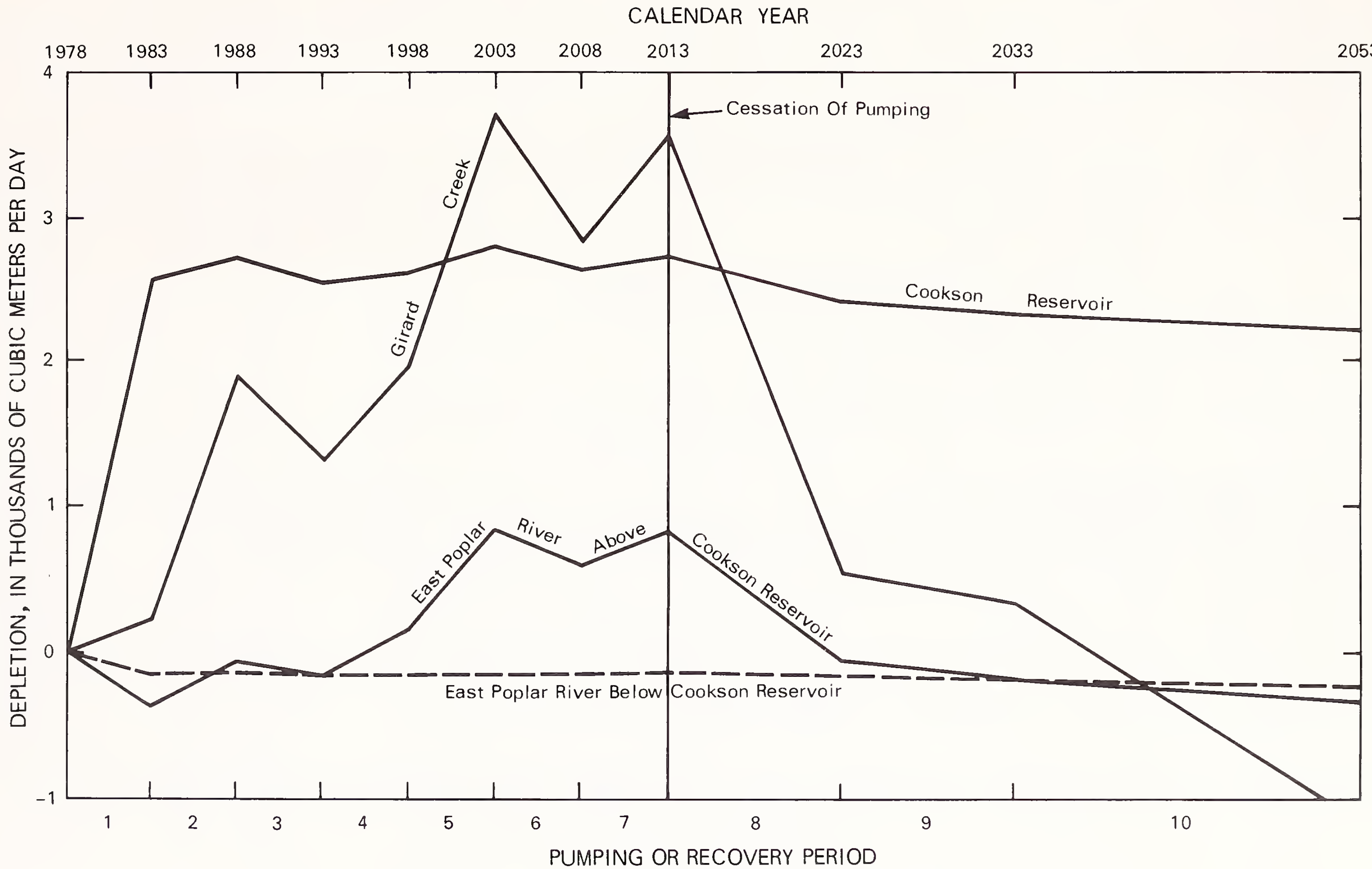


Figure 18.--Predicted depletion of major streams and Cookson Reservoir, upper Poplar River Basin, Saskatchewan and Montana.

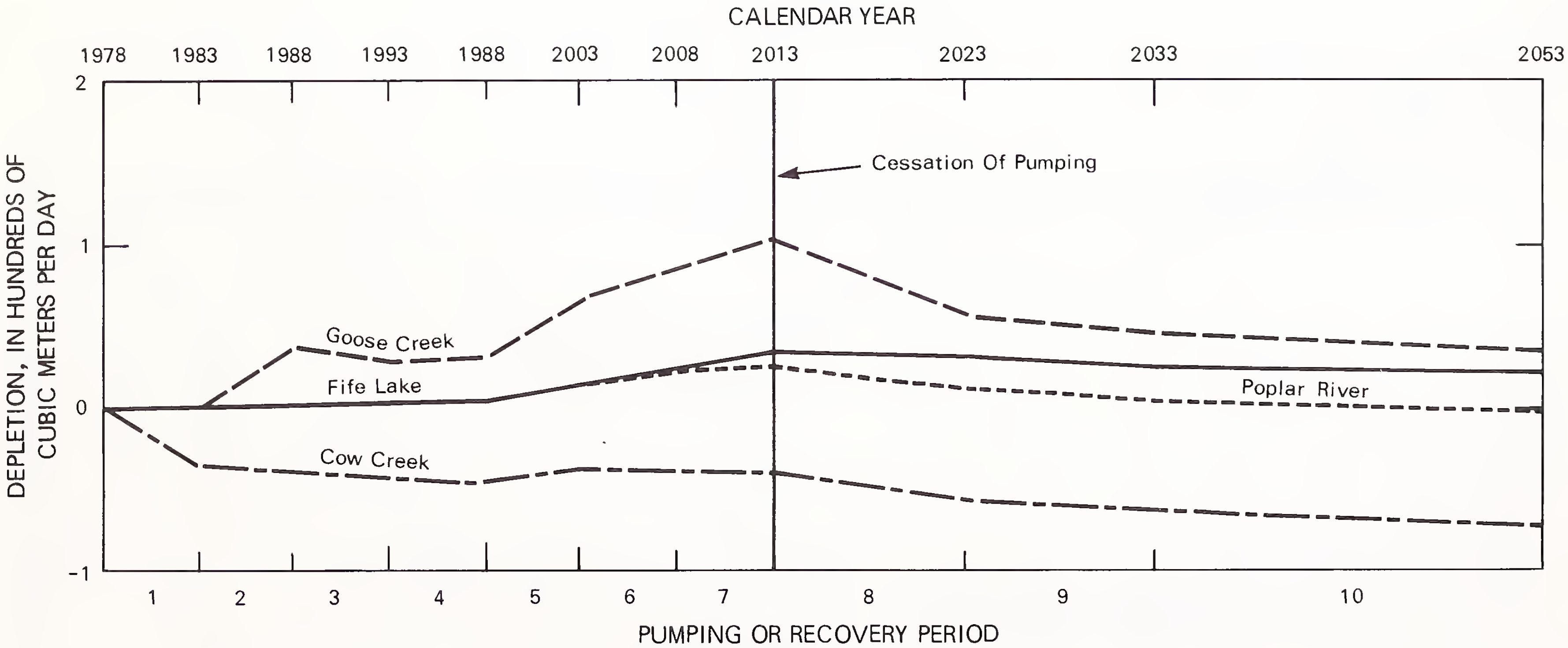


Figure 19.--Predicted depletion of minor streams, and Fife Lake, upper Poplar River Basin, Saskatchewan and Montana.

These residual declines will gradually be further reduced provided that large-scale pumping does not again occur.

The model calculates a predicted cumulative mass balance that summarizes the combined effects of pumping and reservoir leakage on streamflow and aquifer storage. At the end of pumping period 7, the depleted aquifer storage is about 50 percent of the pumped volume. The remaining pumped volume was supplied by reservoir leakage and stream depletion.

In conclusion, the SPC Power Plant and the surrounding areas are underlain by a series of hydraulically connected aquifers. Plant operations will require dewatering wells that will be pumped for 35 years as well as a surface reservoir for plant cooling purposes. The dewatering wells discharge the Hart coal aquifer and Cookson Reservoir recharges a valley-fill aquifer. Drawdown of the water level in the coal aquifer is sensitive to recharge from adjacent aquifers. Long-term dewatering by wells and recharge from the reservoir will cause changes in the water levels in all aquifers that lie above the Bearpaw Formation in the SPC plant region. The effect on the hydraulic potential of pumping or leakage from the reservoir or Girard Creek will be almost instantaneous. However, physical transport of water and dissolved constituents through the formations to the mine dewatering wells will be extremely slow (less than 10 m/yr). Analyses indicate that of the entire volume of water to be pumped by the dewatering wells during the 35-year production period, 50 percent will be derived by depletion of ground-water storage, 27 percent by depletion of water from Cookson Reservoir, and 23 percent by depletion of Girard Creek. Minor depletion of streams that drain into Montana is predicted only for Goose Creek and the Poplar River. Predicted depletion of ground-water and surface-water resources presumes that: (1) dewatering wells will be pumped at rates not deviating to a great degree from those scheduled; (2) Girard Creek will continue to flow and remain hydraulically connected to underlying aquifers; and (3) that Cookson Reservoir will remain at a full level and will not be sealed by fine sediment. Any significant deviation from these presumed conditions will affect the predicted pattern and also the conclusions presented in this report. Water-level declines will slowly recover and surface-water depletion will slowly diminish for many years following the cessation of pumping. Water-level rises and streamflow gains due to Cookson Reservoir will continue as long as the reservoir remains intact and leaks into the valley-fill alluvium.

Additional sensitivity runs of the finite difference (three-dimensional) ground-water model were made to provide more detailed information. The sensitivity runs were used to test the importance of uncertainties in model data, errors inherent in the model, and possible changes in stream and reservoir management. Changes were implemented for the entire simulation period for each run. Tested uncertainties and errors include:

1. Along Girard Creek Valley the transmissivity and storage properties of layer 4 were changed to conform with those of glacial till, as shown in Table 5. However, the ratio of horizontal to vertical hydraulic conductivity for the till was maintained at 1000:1 rather than 10:1.

Resulting vertical hydraulic conductivity of the till in the valley was 9.8×10^{-8} m/d. This analysis presumed that the hydraulic continuity of the upper Ravenscrag Formation was provided across the valley by deposits of glacial till under the valley-fill alluvium. Results indicated that depletion of Girard Creek was reduced substantially and depletion of other creeks increased slightly. Ground-water storage was decreased about 30 percent more than previously reported at the end of period 7, but changes in predicted drawdown and stream depletion in Montana were negligible.

2. Along Girard Creek Valley, layer 5 was eliminated and the creek and alluvium were incorporated into layer 4, directly above the Empress Group of layer 3. However, the ratio of horizontal to vertical hydraulic conductivity for the alluvium was maintained at 1000:1 rather than 10:1. Resulting vertical hydraulic conductivity of the alluvium in the valley was 2.5×10^{-3} m/d. The resulting depletion of Girard Creek was more than doubled and drawdown was reduced in all layers. Under these conditions, well pumping rates would have to be increased in order to induce required drawdown. Greater depletion of Girard Creek would be offset by greater contributions to the creek from well discharge.

3. Girard Creek was eliminated as a perennial stream and Cookson Reservoir was eliminated as a source elevated above the general potentiometric surface of the aquifers. However, the East Poplar River was retained as a perennial stream. This analysis indicated a 54 percent increase in ground-water depletion and a 60 percent decrease in surface-water depletion at the end of period 7 compared to the results presented previously. Drawdown was greater in all layers in Saskatchewan; however, the predicted change in stream depletion and drawdown was very small in all layers in Montana at the end of period 7.

4. All transmissivity values of layer 4 were reduced 50 percent to test the model error in assuming that the transmissivity of layer 4 will remain constant, even though layer 4 will be dewatered near the pumping wells. The vertical hydraulic conductivity of layer 4 was not adjusted. Resulting changes were minor in Saskatchewan and negligible in Montana.

5. Anisotropy in transmissivity for layer 4 was newly simulated as for layer 3, with transmissivity reduced 50 percent in the NE-SW direction. Resulting changes were minor in Saskatchewan and negligible in Montana.

6. Anisotropy in transmissivity for <u>all</u> layers was simulated with transmissivity reduced 50 percent in the NE-SW direction. Resulting changes were minor in Saskatchewan and negligible in Montana.

Potential Impact of SPC Operations on Ground-Water Chemical Quality

Reservoir

For the purposes of the GWQQC report the long-term chemical quality of the water in Cookson Reservoir will be assumed to approximate the reservoir quality range as estimated by the SPC (Supplementary Report, March 1978). It should be mentioned, however, that the Plant, Mine, and Reservoir Committee (of the IPRWQB) has indicated that these estimates may be somewhat low particularly in the case of boron. The potential impact of the reservoir on overall ground-water chemical quality is anticipated to be extremely dependent on the capacity of the aquifers to mediate or buffer any variation in the chemical quality of recharge water. The principal natural ground water recharge (prior to Cookson Reservoir) in the Poplar River Basin was infiltration of snowmelt, a characteristically dilute water with a relatively low pH (5.5 to 6.5) when compared to the pH range of most ground water. The ability of the natural subsurface system to alter the chemical composition of precipitation is obvious since the chemical composition of ground water is considerably different than that of precipitation. Precipitation recharge to the ground water can be altered by prolonged surface flow and possible evaporation and concentration effects. However, the bicarbonate-buffered system over most of the Interior Plains Region tends to mask these perturbations. An exception is localized extreme evaporation in closed or inland drainage basins which may give rise to saline seep areas. The overall geochemical model and carbonate buffer system attributed to the Poplar River Basin is discussed in more detail in the section concerning the model of the geochemical system.

Concerning the overall chemical quality of the ground water affected by reservoir recharge, the carbonate buffer system will likely limit any overall geochemical influence to minor fluctuations around the theoretical saturation limits for the carbonate minerals. This change will be limited primarily to the units overlying the Ravenscrag Formation. This will not be the case for chemical constituents that are conservative in ground water such as nitrate and boron. The reservoir chemical quality is more similar to ground-water chemical quality than to that of average precipitation. The perturbation in natural ground-water chemical quality due to the reservoir will probably be less than natural temporal variations (Figure 7).

Although reaction rates may possibly be a factor in the interaction between the reservoir and the ground water, the similarity of the chemical quality of both waters is expected to reduce this aspect to minor significance. If, however, reaction rates are sufficiently low, then that part of the ground-water system likely to be most significantly affected by the reservoir will be the relatively fast subsurface flow system around and beneath Morrison Dam. The springs and seepage on the immediate downstream side of the dam would, in this case, eventually acquire a chemical quality similar to that of the reservoir. On the basis of experience in other areas in the Interior Plains Region, as well as the overall similarity in quality of reservoir water and shallow ground water, it is unlikely that the overall chemical composition of the seepage water would vary significantly from that of normal ground water. However, conservative constituents such as boron and nitrate,

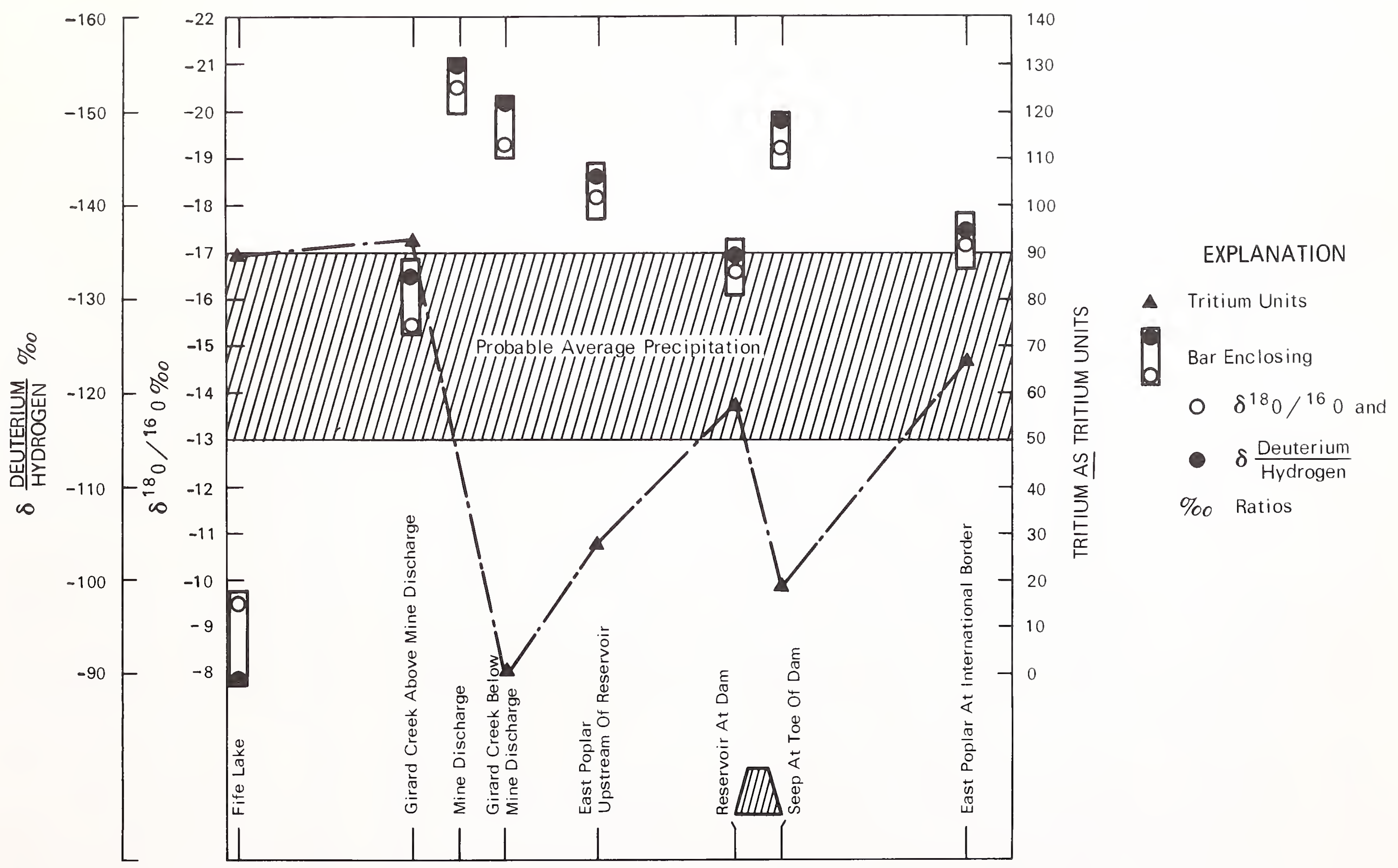


Figure 20.--Diagram showing variations in D/H and O^{18}/O^{16} and tritium values resulting from differences in water sources.

which are much less subject to solubility or ion-exchange controls in the subsurface will tend to approach reservoir concentrations in both the near-dam seepage as well as in the shallow ground-water flow system dominated by induced reservoir recharge. Phosphate is extremely sensitive to solubility controls in these typically alkaline, high calcium ground waters, and most of the phosphorus entering the ground-water regime is likely to be precipitated as apatite-like minerals ($Ca_5(PO_4)_3(OH, Cl, F)$).

Temperature effects due to the use of the reservoir as a cooling impoundment were also considered. The temperature rise will affect the precipitation-dissolution reactions in the ground-water system. The probable temperature increase in recharge water from the reservoir is expected to be approximately 6°C. The equilibrium solubility computer model (Table 6) was run at field temperature plus 6°C for each of the samples. Although minor differences in the saturation state of some of the minerals occurred, in no instance was the logarithmic value of the saturation index changed by more than 0.3, a numerically insignificant value in this type of calculation.

An attempt was made by the GWQQC to determine by means of isotope data analysis if the seepage water at the toe of Morrison Dam was reservoir water, emerging reservoir water, or was natural ground water. The oxygen-18 and deuterium results shown in Figure 20 indicate that most of the present seepage is ground water that is likely being forced to the downstream seepage area at a much higher flow rate than normal due to the imposed hydraulic gradient of the reservoir. Cookson Reservoir thus appears to be causing natural ground water to emerge at the toe of the dam at much higher rates than would seep to the East Poplar River in this vicinity under prereservoir conditions. The measurable tritium in the seepage-water sample can be interpreted as either a minor contribution of reservoir water to the underflow seepage or, most probably, as a small amount of relatively shallow flow directly through or immediately around the dam. There are definite seepage areas which are higher on the face of the dam than the major underflow seepage visible at the toe of the dam. It is possible that these seepage faces are the source of the minor amount of tritium observed in the seepage sample.

A further effect of Cookson Reservoir on overall ground-water chemical quality is to divert normal baseflow away from Girard Creek and the East Poplar River. This effect is to increase the length of the subsurface flow path that the ground water must follow before discharging below Morrison Dam. The increased length of flow path could result in a longer transit time and higher dissolved-solids concentration of the water. However, the increase in the dissolved solids concentration is expected to be within the limits of the natural variation. Except in the immediate vicinity of the reservoir, the redirected flow due to the reservoir-induced ground-water mound is likely to remain within the formations from which the flow originates. Over most of the study area the ground-water chemical quality within the individual formations will therefore remain similar to prereservoir conditions.

Interformational flow, because of the reservoir mound, is likely to occur primarily in the vicinity of the reservoir where the vertical gradients are highest. The reservoir-induced interformational flow will likely be downwards and may cause some of the shallow, higher-quality ground water in the drift material to enter the Ravenscrag Formation. It is expected that the carbonate buffer system will chemically alter, within a short distance, the quality of the induced flow and render it essentially indistinguishable from the chemical composition of normal Ravenscrag Formation ground water. The same buffer effect may occur as water moves upward into the Hart seam because of mine dewatering. Changes in the concentration of conservative constituents such as boron, are not likely to be noticeable because the variation in concentrations between formations is within the range of natural temporal variations within a single formation.

In summary, the presence of the reservoir is expected to cause a slight degradation in overall ground-water chemical quality, although in most instances the change will be indistinguishable from normal temporal variations in ground-water chemical quality. The most noticeable effect will be in the shallow drift aquifers near Cookson Reservoir where the chemical quality under natural conditions is generally better than that of the reservoir. The water in these aquifers could conceivably undergo eventual deterioration equivalent to that anticipated for Cookson Reservoir. The effect will be limited primarily to the area of influence of the ground-water mound on the natural flow system, although some minor effects throughout the shallow flow system are possible. The effect will be restricted to several kilometers from the reservoir and extend only slightly into Montana.

The influence of the reservoir on the shallow ground-water system could also cause a rising water table with an increase in the number of salinized and saline-seep affected areas. The rising water table would first intersect low-lying areas and the evapotranspiration of the resulting moisture could leave an increasing number of salt-affected low areas. It should be noted that numerous saline zones are already present along the margin of the stream valleys.

The chemical quality of ground water in the Empress Group, Ravenscrag, and Frenchman Formations is not expected to be significantly altered, even though water levels in these aquifers are presently rising near Cookson Reservoir. An exception could eventually occur near the reservoir in the upper part of the Ravenscrag Formation and in the Empress Group where conservative constituents such as boron or nitrate may eventually approach concentrations found in the reservoir.

Ash Lagoons

The currently proposed location of the ash lagoons is southwest of Cookson Reservoir. The ash lagoons will utilize the till as a base and reworked till as retention dikes. The most recent drilling operations in the vicinity of the ash lagoons indicated that 14 to 20 meters of till overlies 2 to 8 m of preglacial sand and gravel (Empress Group),

and that the Empress group in turn rests on the Ravenscrag Formation. Recent drill holes indicate that the till is heterogeneous and contains more coarse grained and permeable zones than previously assumed. The presence of these more permeable zones emphasizes the conclusion of the GWQQC that a lining of some type is essential for adequate retention of potential contaminants in the ash lagoon water. The reason for this concern is that the water in the ash lagoons will not only be of poorer chemical quality than the reservoir or normal ground water, but also may have contaminant-level concentrations of chromium, boron, and nitrate. Although high concentrations of molybdenum are not expected, an imbalance in the copper-molybdenum of the soil giving rise to molybdenosis in cattle (see page 22) is a possibility and is a further reason for advocating an adequate lagoon lining.

The water in the lagoons is expected to have a relatively high initial pH of about 11 or 12. Although there is some opportunity for buffering and pH reduction in the lagoons as a result of reactions with atmospheric carbon dioxide the GWQQC believes that the buffering capacity in the tills substantially exceeds that for the atmospheric reactions. It is anticipated that most of the pH reductions from 11 or 12 to a value of approximately 8 will take place during downward movement of the leachate through the till. The effective mechanisms will be (1) precipitation of metal hydroxides and carbonates (2) coprecipitation of such contaminants as chromium and arsenic, and (3) the anion (hydroxyl) exchange capacity of the till which is probably of the order of 1 to 10 meq/100g.

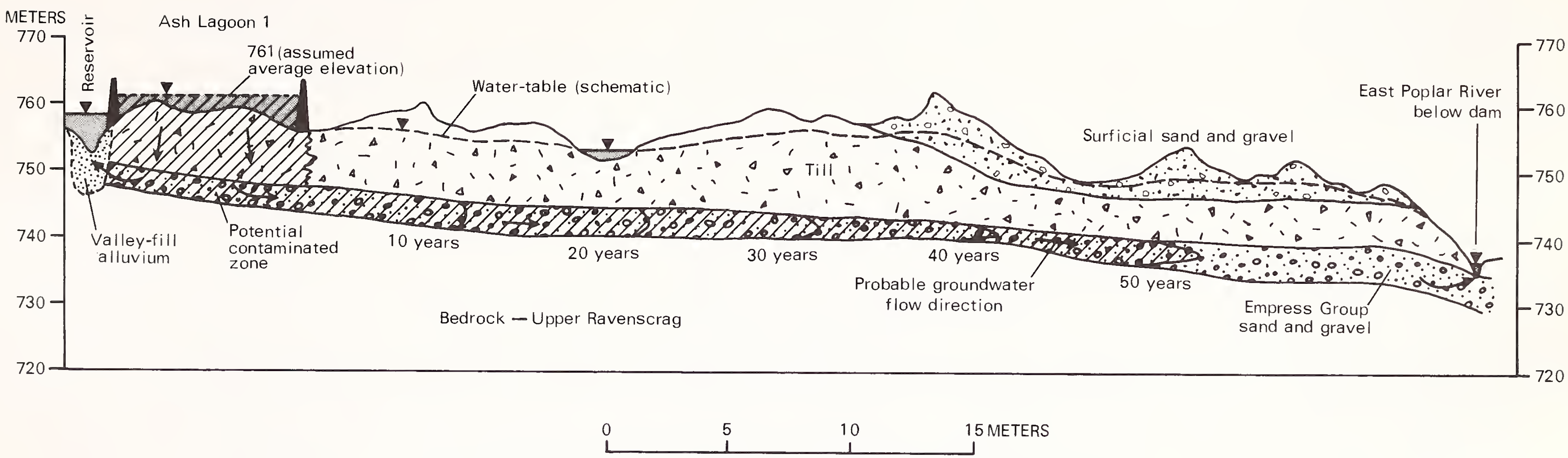
The principal solubility controls on the mobility of the potential contaminants in the leachate are the oxidation-reduction conditions and the pH of the solution. Most of the potential metal contaminants remain somewhat soluble as anionic oxyions in higher pH waters, and relatively oxydizing environments, (for example, CrO_4^{2-}, MoO_4^{2-}, $HAsO_4^{2-}$, SeO_4^{2-}, and H_2BO_3); however, in reducing environments their solubility is less and precipitation as sulfides could result (for example FeAsS, MoS_2). The actual mobility of metals in relatively reducing ground water with low pH could be further decreased by the formation of cationic rather than anionic compounds (for example $Cr(OH)_6^{3+}$ rather than CrO_4^{2-}), which may result in their sorption on cation exchange sites. Some of the metals also are likely to be tied up in organic complexes or as uncharged ion pairs, resulting in their relative unavailability for ion exchange or other attenuation processes.

Solubility and sorption controls notwithstanding, the uncertainty concerning trace element mobility in the ground-water system suggests that they should be considered as remaining in solution and moving unattenuated with the ground water. Although in alkaline environments most metallic cations would be expected to precipitate, anionic species such as molybdate, borate, selenate, chromate, arsenate, and vanadate will usually remain in solution. There is reason for concern because many of these elements exceed the state, provincial and federal government recommended concentration levels well below their theoretical solubility limits. In the remainder of this discussion the ash lagoon leachate will be considered to contain relatively conservative contaminants, not only because trace element mobility controls are uncertain but also because of the finite capacity of the clays in the till to provide ion exchange sites.

The most likely scenario that can be developed concerning the ash lagoons consists of downward leakage to and subsequent travel through the Empress Group aquifer. Discharge to surface water would be primarily to the East Poplar River below Morrison Dam. Additionally, because of the higher water levels in the ash lagoons, a part of the leachate will travel in a north-northeasterly direction from the lagoons and discharge into Cookson Reservoir. Figure 21 is a schematic northwest-southeast cross section through the area of the ash lagoons showing likely directions of subsurface water movement. The ash lagoons will produce a further ground-water mound superimposed on the southwest edge of the Cookson Reservoir ground-water mound. The result of the ash lagoons mound will be to eliminate any subsurface flow from the reservoir along most of its southwestern side and to saturate the underlying Empress Group sands and gravels and any intertill sand or gravel lenses with water of ash lagoon quality. This means that the water emerging in the East Poplar River from the western side of the former reservoir-mound flow system will no longer be of reservoir quality but of ash lagoon quality. Conceivably, this effect could cause a significant deterioration of East Poplar River water crossing the International Border.

The scenario presented above assumes that vertical flow rates through the till will provide a substantial part of the horizontal flow through the Empress Group. The following calculations illustrate the likely order of magnitude of ground-water flow from the ash lagoons through the till to the Empress Group. The conclusion is that ash lagoon leakage can be significant and that leakage from the till can provide substantial flow to the Empress Group. The hydraulic parameters used for the till in this calculation are somewhat different than those used in the model calculations (Table 5). In the case of the model, the till was considered to be everywhere uniform with no variation in either horizontal or vertical hydraulic conductivity. The single vertical hydraulic conductivity value so assigned was intended as a composite value representative of the real variations in vertical conductivity within a typical vertical till section. This composite value also carried with it the assumption that the real till section was reasonably thick and therefore included a typical sequence of permeable and less permeable layers. The finite-difference model calculation was thus based on the assumption of an "average" till layer. The lagoon leakage calculations, on the other hand, were made on an anticipated "most severe case" basis rather than an "average case" basis since it is possible that the lagoons in an unlined state could be situated on a thickness or textural variation of glacial material which might not be representative of an average or typical till section. Information provided by the Plant, Mine, and Reservoir Operations Committee (of the IPRWQB) suggests that in the case of the ash lagoons these most severe case parameters are in fact more appropriate than the average values used in the finite-difference hydrologic model and that even these parameters may be somewhat conservative. The following calculations indicate that lagoon lining is necessary to reduce the ground-water contamination potential to acceptable levels.

The vertical hydraulic conductivity of the till, K_T, is estimated



Schematic diagram of potential subsurface contamination due to Ash Lagoon leakage

Figure 21.--Schematic diagram of potential subsurface contamination from ash lagoon leakage. Arrows show probable direction of water movement.

to be about 10^{-8} m/s and the area covered by a typical lagoon is taken as 8×10^5 m^2. The hydraulic gradient, dh/dl_T, across the till is estimated as about 0.5, the difference between the ash lagoons water level (the head existing at the top of the till) and the reservoir water level (the maximum head likely in the Empress Group sands and gravels below the ash lagoon) divided by the vertical distance between the base of the lagoon and the top of the Empress Group. The total downward flow through the till, Q_T, was calculated using Darcy's law:

$$Q_T = A_L K_T (dh/dl_T) \tag{3}$$

$$= 8 \times 10^5 \text{ m}^2 \times 10^{-8} \text{ m/s} \times 0.5$$

$$= 0.004 \text{ m}^3\text{/s} = 350 \text{ m}^3\text{/d}$$

The value of Q_T was compared with the estimated Empress Group flow rate calculated below.

A probable flow rate, Q_E, in the Empress Group (which is approximately 3 m thick) can be calculated on a unit width basis by assigning a hydraulic conductivity for the Empress Group, K_E, of about 10^{-4} m/s, and a hydraulic gradient, dh/dl_E, of 0.003 (the difference between reservoir level and average river level from the dam to the International Border divided by the horizontal distance between the lagoon and the East Poplar River). The flow calculation in this case is for a vertical section one meter wide of the Empress Group, perpendicular to the direction of flow, and is given as:

$$Q_E = A_E K_E (dh/dl_E) \tag{4}$$

$$= (1 \text{ m} \times 3 \text{ m}) \times 10^{-4} \text{ m/s} \times .003$$

$$= 9 \times 10^{-7} \text{ m}^3\text{/s} = 0.08 \text{ m}^3\text{/d}$$

per meter width of discharging aquifer.

In order to relate this flow rate to the ash lagoon recharge rate through the till, the total discharge from the Empress Group to the East Poplar River between Morrison Dam and the International Boundary must next be calculated. The estimated length of this stream reach is

4800 m and, since discharge occurs on both sides of the stream, there are 9600 m of discharging length. Thus, the total discharge, Q_p, from the Empress Group to the East Poplar River between the dam and the border can be calculated as:

$$Q_p = 9 \times 10^{-7} \, \frac{m^3/s}{m} \times 9600 \text{ m} \tag{5}$$

$$= .009 \text{ m}^3/\text{s} = 750 \text{ m}^3/\text{d}$$

This value is, of course, only approximate but is of the correct order of magnitude for minimum flow values observed at the International Border since the filling of Cookson Reservoir. It must be noted here that this calculated flow rate is independent of dam underflow or riparian outlet. On a simple most severe case comparison as presented above, therefore, all of the downward leakage could be diverted laterally within the Empress Group and eventually be discharged into the East Poplar River below Morrison Dam. The most severe case, however, represents a rather unlikely combination of circumstances. The possible creation of a ground water mound beneath the ash lagoons and the effects of permeability anistropy in the till would both tend to divert leakage laterally through the till towards the reservoir and in other directions not leading to direct discharge in the East Poplar River below Morrison Dam. Any limitations on the capacity of the Empress Group to transmit both the usual ground water flow and a substantial flow contribution from lagoon leakage would have a similar effect. In brief, we feel that a part of the lagoon seepage will almost certainly be directed towards Cookson Reservoir and that the actual direct lagoon seepage contribution to the East Poplar River below Morrison Dam will probably be appreciably less than 350 m^3/d.

A schematic illustration of the anticipated ground-water flow and contaminated zones in the Empress Group also is presented in Figure 21. The calculations were completed using a one-dimensional version of the conservative contaminant transport equation with a reasonably small dispersivity of about 0.5 m, an Empress Group porosity of 0.3, and a boundary condition of continuous contaminant or ash lagoon input. This small value was selected because the Empress Group is thin. The contaminated zone within the Empress consists of: (1) a fully contaminated region extending outward from that part of the formation into which the ash lagoon leachate is infiltrating; and (2) a "contaminant front" in which contaminant concentration varies from zero to 100 percent. As time progresses, the contaminant zone spreads out from the area of infiltration and the spread of the contaminant front becomes greater in the direction of flow. This change in the contaminant front is schematically illustrated by the spread of the leading edge of the contaminated zone in Figure 21. Further dilution (although probably insignificant) is likely within the contaminated zone because of precipitation discharge through the till along the length of the flow path in the Empress Group. The travel times indicated in Figure 21 are approximate.

Figure 21 also schematically illustrates the likelihood of flow reversal in the till and Empress Group near the reservoir and potential leakage of the ash lagoons to the reservoir. It is not anticipated that this leakage will significantly alter the reservoir chemical quality because it will be minimal compared to the decant water flow from the ash lagoons. The ash lagoon decant water has already been taken into consideration in computations of reservoir quality, by the Plant Mine and Reservoir Operations Committee of the IPRWQB.

Complete elimination of leakage from the ash lagoons could presumably be accomplished using an artificial lining material such as commercially available plastic used for lining irrigation canals, municipal reservoirs, and landfill areas. Because subsurface leakage is not included as a factor in the lagoon operation, the life expectancy calculations estimated by the Plant, Mine, and Reservoir Operations Committee would remain the same. A less expensive method of reducing leakage would be to place a clay (bentonite) and sand mixture over the base of the lagoons before operations commence. An inter-granular hydraulic conductivity for a well-mixed and properly compacted bentonite-sand mixture lining would likely be of the order of 10^{-10} m/s or less. The effect of reducing the limiting hydraulic conductivity by two orders of magnitude is obvious if the appropriate substitutions are made in the volumetric leakage-rate calculations in equation 3. The calculated leakage rate would then be reduced from 350 to 3.5 m^3/d, or less than half of one percent of the estimated discharge in equation 5 from the Empress Group between Morrison Dam and the International Border.

The ash lagoons may cause an even greater diversion of ground-water flow lines than have already occurred because of Cookson Reservoir. It is expected, however, that the influence of the ash lagoons will not be of sufficient magnitude to create any trans-boundary ground-water flow from Canada into the United States. This conclusion is based on the finite-difference model results for long-term influence of the reservoir on the ground-water system. The results essentially indicate no change in the direction of ground-water flow near the International Border. The direction of ground-water flow at the border is parallel to the border and towards the East Poplar River. Although quantitative modeling of lagoon effects has not been performed, lining of the lagoons can also be expected to reduce substantially the effect that the mounds may have on the subsurface flow system, as well as to reduce their contamination potential.

Ancillary Mine Operations

Other potential sources of ground-water contamination from the immediate vicinity of the SPC plant include the coal storage piles, the plant sewage lagoons and associated possible sod-farm effluent spray-irrigation operation, the cooling water channel, the evaporation pond for coal-pile runoff, and the garage and machine shop facilities.

Coal Piles

The coal storage piles will probably be a minor potential source for surface-water contamination, easily controlled by appropriate

surface drainage measures. The most likely chemical quality of the water resulting from precipitation on, and percolation through, the coal piles will be a relatively oxidized version of the present Hart seam ground water. The coal pile water may possibly have a lower pH due to lack of carbonate, and a higher sulfate concentration because of aeration of the piles and the potential for continual iron sulfide oxidation. The results of a national study questionnaire in the United States (Weeter, 1978) indicated some potential detrimental effects from most coal piles, with some site-specific cases related to increases in heavy metals, a few instances of excessive sulfate, and some tendency for oil and grease to occur at above-background concentrations. Sulfide oxidation may cause minor acidic drainage from the coal piles at the SPC Poplar River Plant. Any sub-surface movement of the acid drainage would, however, subject the water to almost immediate pH buffering by the carbonate system. If the coal pile drainage water is diverted to the ash lagoons, further neutralization of the water would occur.

Exposure of the shales associated with the coal to oxidizing conditions also could result in nitrification of some exchangeable ammonium on the clay minerals with a resultant increase in nitrate in the drainage water. Power and others (1970) indicated that nitrate concentrations were 10 to 30 mg/L in oxidized drainage water from Fort Union spoil piles. The possible increase in nitrate from coal- and spoil-pile drainage should be considered by the other committees of the IPRWQB in their assessment of drainage control and diversion procedures around the mine and plant site.

It is obvious that any of the ancillary facilities such as the coal piles or sewage lagoon should be located on fine-grained tills preferably with a lining or at least having a reworked clay base. Sites containing coarse-grained materials should be avoided as these are possible ground-water sources in the till and may be sensitive to contamination from the piles.

Sewage Lagoon

The sewage lagoon probably will be operated in the standard double-lagoon anaerobic-aerobic system. There is little evidence of nitrate ground-water contamination from properly located and constructed lagoons of this type in the Interior Plains Region. The combined effects of denitrification in the retention lagoon as well as organic-nitrogen and ammonium nitrification generally serve to reduce the nitrogen levels in the effluent. Moreover, bacteria of fecal origin are generally reduced to acceptable levels in properly operated retention lagoons. Sewage lagoon facilities situated on coarse-grained material can, however, be a significant source of nutrient as well as bacterial and viral contamination in the ground-water system. Thus, to avoid contamination of ground water, the sewage lagoon should be located over the fine-grained till of the area, and have a lining similar to that

recommended for the ash lagoon. If the water entering the sewage lagoons has undergone chlorination, there also is the potential for ground-water contamination by chlorinated hydrocarbons.

Spray-Irrigation Of Sod Farm With Sewage Effluent

The effluent decant from the sewage lagoon may be used to spray-irrigate a small sod farm located southwest of the plant site. In terms of contamination of ground water, nitrate is the most troublesome constituent. In most instances, however, the nitrate levels of spray-irrigation effluent are well below 10 mg/L nitrate as nitrogen. Most nitrate is lost to crops with only a minor percentage remaining in the downward leaching component of the irrigation requirement. Phosphorus as phosphate will be precipitated due to solubility controls. Bacterial contamination in spray-irrigation operations is usually minimal since the previous lagoon treatment should have reduced the bacterial concentration to acceptable levels prior to spraying. Although it is possible for viruses to be transported in ground-water systems, the mortality rate of most viruses and bacteria is high during airborne travel from the sprinkler nozzles as a result of exposure to oxygen and the ultraviolet rays of the sun. The operation of the sod farm is considered viable from a ground-water quality standpoint provided the grass crop, with its high potential for nutrient and even partial trace-metal utilization, is located on fine-grained till areas. There are some instances of successful spray-irrigation practices on sandy soils, but more control on irrigation procedures and timing is required than on fine-grained till areas.

Garage and Machine Shop Effluent

Effluents from garage and machine shop operations at the SPC power plant could present one of the larger potential contamination hazards, principally from those contaminants having a hydrocarbon origin such as gasoline and lubricant oil. Hydrocarbon contamination of ground water is rapidly becoming a principal cause of ground-water degradation throughout Canada and the United States, and considerable care should be given to the operation and location of such facilities as the garage and machine shops. Used lubricant oil should be recycled and any disposal should preferably be by means of combustion rather than by drainage to seepage pits which can contribute to ground-water contamination.

The location of any bulk fuel and lubricant storage tanks is of critical importance with respect to potential ground-water contamination in the event of leakage or failure of the tanks. Storage should preferably be above ground on fine-grained material with sufficient surface-diked or bermed capacity to contain all potential leakage. Alternate storage facilities for escaped hydrocarbon should be available, as hydrocarbons must not drain to the subsurface from within the

bermed area. Coarser-grained materials such as sands and gravels should be avoided in the siting of either tank storage or shop and attendant drainage facilities.

Cooling Water Channel

The Plant, Mine, and Reservoir Operations Committee (of the IPRWQB) has suggested that the cooling water used by the plant may require chlorination. This possibility and the consequent likelihood of chlorinated hydrocarbons has presumably been considered by that committee in the total reservoir water-quality calculations. Although there will be some dilution capacity in the reservoir for such contaminants, it is apparent that seepage from the cooling water return channel between the plant and the reservoir represents a further potential source of ground-water contamination. For this reason, it is recommended that any surface flow channels constructed from the plant to the reservoir or any of the retention or disposal lagoons be located, if possible, in fine-grained till. Should exploratory drilling or construction indicate the presence of extensive coarser-grained material in the line of canal or ditch then clay or plastic liners are recommended.

Mine Dewatering

Throughout the 35-year period of mine dewatering, ground water pumped from the Hart coal seam will continue to be discharged to Girard Creek. As shown in Table 7, the present quality of the mine water is similar to that of natural base flow of the Poplar River at the International Border. At times the natural base flow water has higher boron concentrations and generally is of poorer quality than the mine water. The mine discharge will continue to flow into Cookson Reservoir where it will be diluted by stored surface runoff. Digital simulation of ground-water flow patterns indicates that as mining operations approach Fife Lake, seepage from the lake will increase, possibly resulting in increased boron concentrations in ground water discharged from the mine dewatering wells. Analysis of chemical quality and isotope data (Figs. 20 and 22) indicate that at present only a small proportion of water from Fife Lake drains to Girard Creek. As can be seen from Figures 20 and 22, both deuterium/hydrogen, and oxygen-18/oxygen-16 ratios are distinctive for Fife Lake because of the large amount of evaporation from the shallow lake. In the future if increasing seepage from Fife Lake to the mine dewatering area is suspected, these isotope ratio methods may be useful detection techniques.

Results of the layered finite-difference mathematical model indicate that, during the period when the effects of pumping to dewater the sites to be mined are greatest, over 80 percent of the ground water pumped will come from formations overlying and underlying the Hart

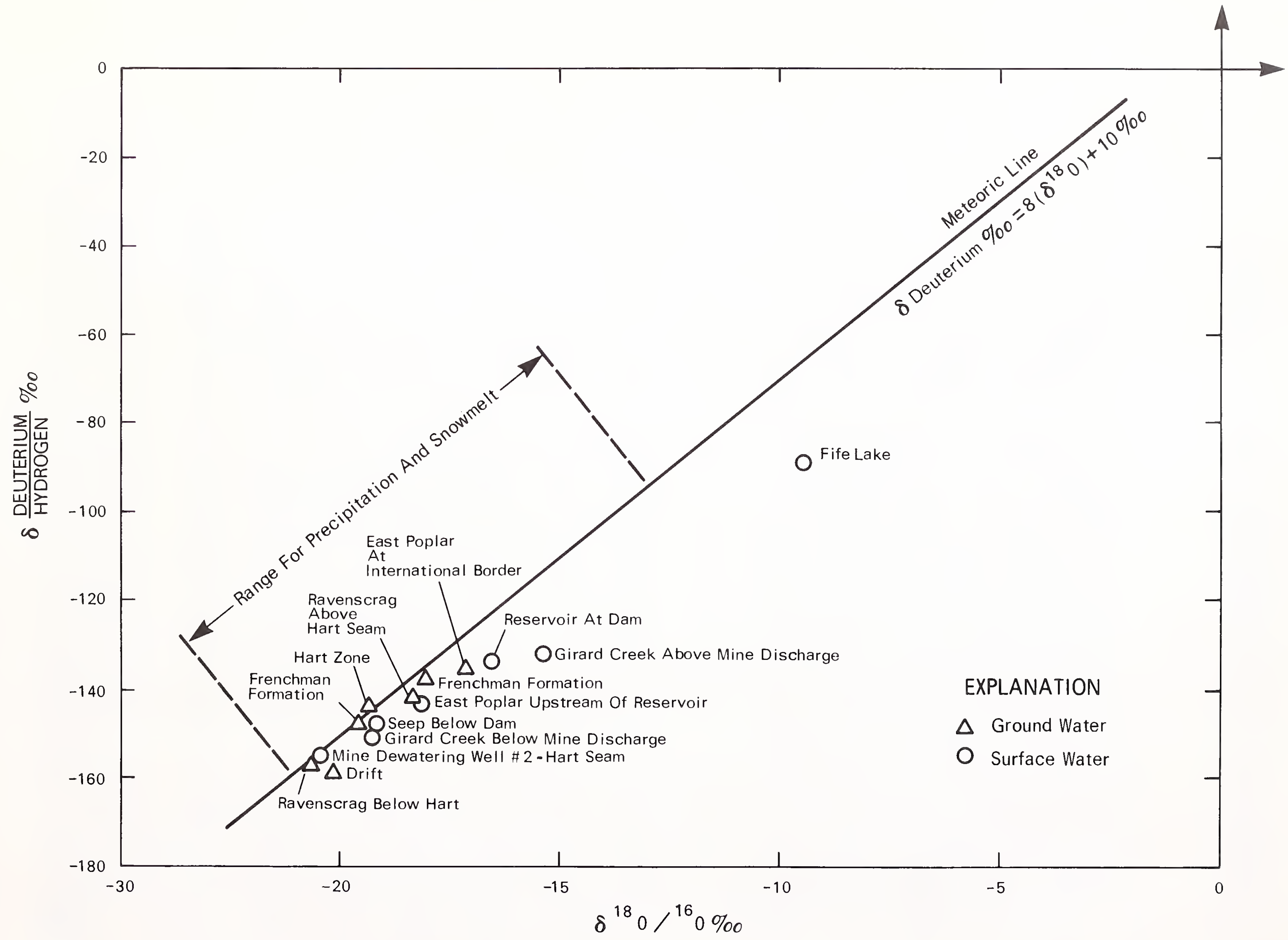


Figure 22.--Diagram showing relation of D/H and O^{18}/O^{16} among waters collected by GWQQC in May 1978.

coal seam. Less than ten percent will come from the Frenchman Formation. Except under conditions in which Fife Lake may leak to the dewatering wells, it will be difficult to detect changes in the chemical quality of the water due to leakage from formations adjacent to the Hart coal seam. This is because of the similarity of the chemical quality of water in the Hart coal seam to that in adjacent formations.

As mining progresses, spoil piles in the vicinity of mine dewatering areas could have an effect on the quality of water discharged from the mine dewatering wells. Generally water infiltrating spoil piles and ground water flowing through spoil piles are deteriorated in quality, with increases in dissolved solids and trace-metals the most notable effects. The type of material placed in the spoil piles and their permeability will determine the ultimate effect on the chemical quality of mine discharge water. Experiments with various methods of spoil placement may aid in reducing deleterious effects on ground-water quality. One method may be to place the most reactive spoil materials (generally organic shales containing pyrite) at the bottom of the fill. This would assure that most of the oxygen in water infiltrating the spoils would be consumed before contacting pyritic material.

During mine dewatering operations a cone of depression will be established which will intercept a small part of the ground water that normally flows to Montana. As long as the cone of depression persists, ground water from the mined areas will not move southward across the International Border. Estimates of the rate of recovery of the cone of depression indicate that 45 years after mining and pumping cease the cone will still be recovering. Eventually, however, the movement of ground water in the mined areas will be restored towards the south across the International Border. Calculations of rates of ground-water movement from the mined areas south to the International Border indicate transit times of hundreds of years. Even assuming that the water from the mined area acquired higher concentrations of undesirable constituents, the water would be greatly diluted in transit because of infiltration and dispersion as it moved southward. In addition, it would react with aquifer materials and ground water to reestablish chemical equilibrium with the surrounding ground water and rock. The quality of ground water moving across the International Border will not be degraded as a result of mine dewatering and spoil backfilling operations by the SPC power plant.

Transboundary Effects Due to SPC Influences on Ground Water Chemical Quality

The long-term finite difference simulation indicates that the configuration of the overall ground-water flow system after mining, reclamation, and drawdown recovery, will differ only slightly from that of the premining system except that the ground-water mound created by the reservoir will be permanent. At no time during the mining or post

mining period will there be a change in the principal flow direction of the ground-water system at the border. The conclusion drawn from this prediction is that the direct transborder influences of the SPC plant operation on ground-water chemical quality on the United States side of the International Border will be negligible.

The effect that the mining operation will have on ground-water chemical quality (and in some instances on surface water chemical quality) will be localized in nature. For example, in the vicinity of Girard Creek upstream from the reservoir, the Hart coal seam is currently in hydraulic connection with the Empress Group and the valley-fill alluvium. The mining operations will presumably extend close to the erosional edge of the Hart seam in the Girard Creek Valley. The result will be to replace the Hart seam aquifer and overlying formations with mine spoil material. The spoil material will then be in hydraulic connection with the ground-water system contributing to surface-water flow in Girard Creek. Ground water in the spoil-pile zones is expected to be higher in dissolved solids than natural ground water of the upper Ravenscrag and overlying formations in the same areas prior to mining. Ground water passing through the spoil material and eventually discharging to Girard Creek could, after recovery of the potentiometric surface to premining levels, be of poorer quality than at present. This poorer quality water discharged to Girard Creek could then contribute to degradation of the overall reservoir quality, although it would be subject to mixing with and dilution by surface water already in the reservoir.

Quantification of the change in quality of the ground water contribution to Girard Creek caused by mine spoil effect is difficult since there are no relevant studies pertaining to similar hydrogeologic areas. On a comparative basis, however, it can be stated that the soluble salts in the Poplar River spoil material are similar to that of the subbituminous coal field in Montana described by Van Voast and others (1976). They found that the dissolved-solids concentration of spoil material in water in the Decker, Montana area generally ranged between 3,000 and 3,500 mg/L. This range was within the upper 10 percent of natural ground-water quality values within the region they studied. In the Colstrip, Montana area they found a wider range, between 1,500 and 6,000 mg/L, which was generally within the upper 50 percent of natural regional ground-water values. Some of the conclusions regarding ground-water quality in spoil areas also are applicable to the Poplar River Basin. They are:

1. Mined area ground waters are somewhat more mineralized than those in undisturbed coal beds.
2. Mined area ground waters are chemically more similar to waters in inorganic aquifers than to waters in coal beds.
3. Dissolved solids concentrations of ground waters in mined lands are locally as great at 6,000 mg/L but most are between 1,500 and 3,500 mg/L.

4. The first ground water that enters newly mined spoils dissolves a high percentage of the available salts; subsequent pore volumes of water are progressively less mineralized.

In the Poplar River area conclusions 1 and 2 could be interpreted to suggest that the quality of water in the spoil material will resemble Ravenscrag Formation water; however, the Hart coal seam water and the water in the Ravenscrag Formation are presently very similar in quality and major differences will be difficult to ascertain.

If the geochemical processes alluded to in conclusions 3 and 4 above are applicable to the Poplar River Basin, the result could be a significant spatial and temporal variation in the ground-water quality in the spoil areas.

The conclusions are that the ground-water contribution to Girard Creek may be somewhat higher in dissolved-solids concentration and that spatial and temporal variations can be expected in the quality of discharge from the ground-water system. The major factor influencing the temporal variations in the quality of discharge from the ground-water system will be that the initial water from the spoil may have a higher dissolved-solids concentration than subsequent discharge. There will be some spatial variation as well, because of the changing location of mining and reclamation operations. The end result may be only a minor perturbation on the reservoir chemical quality; however, other committees of the IPRWQB should be made aware of the possibility of deteriorated chemical quality of ground-water discharge to Girard Creek. There is also the possibility that during dewatering operations poor quality ground water that has drained through spoil material adjacent to the dewatering wells could be pumped and discharged to Girard Creek. The effect on chemical quality of flow through the spoil material could perhaps be better evaluated if monitoring wells and piezometers were established in the areas which are reclaimed first, and water samples obtained from these wells for chemical analysis.

More highly mineralized ground water in the reclaimed areas could result in an increase in the number and size of salt-affected land areas. Discussion of the soil-salinization potential in the reclaimed area is beyond the scope of this report because the effects will be limited to the Canadian side of the International Border. However, final recasting and landscaping procedures will strongly influence the shallow-flow systems and salinization potential in the reclaimed areas. This aspect of reclamation is discussed in detail by Moran and others (1978).

Transboundary effects of soil salinization from the SPC power plant are expected to be minimal. This conclusion is based on the finite-difference flow-model predictions which show a maximum water-table rise in the surficial material at the International Border of 0.4 m some

40 years after mine dewatering ceases. The water-table rise is due to the reservoir-induced ground-water mound. Soil salinization could be a potential serious transboundary effect if there were extensive and permeable hydraulically connected zones in the till which were not accounted for in the model. Because of the heterogeneous nature of the glacial deposits an extensive drilling program would be needed to determine if this were the case. It is recommended, therefore, that representative shallow wells at the International Border be monitored regularly for water levels. In addition it also will be necessary to establish control wells for measuring water levels in other parts of the basin to differentiate between the influence of Cookson Reservoir and normal basin fluctuations.

Although the most significant ground-water effect on transboundary chemical quality will be from ground-water discharge to the East Poplar River below Morrison Dam, the changes will likely only be significant during extreme low-flow periods. During low-flow periods most of the flow in the East Poplar River is derived from ground water. At other times changes in the chemical quality of ground water discharging to the East Poplar between the Morrison Dam and the International Border will have a limited effect on the Poplar River chemical quality, because the total discharge at the border will be mostly surface runoff.

Conclusions

The conclusions from this GWQQC study may be conveniently arranged into the following categories: (1) baseline conditions and recent changes; (2) predicted long-term quantity changes; and (3) predicted long-term quality changes. Baseline conditions are those conditions that are judged to have characterized the ground-water systems of the Poplar River Basin (particularly the East Poplar River Basin) prior to construction of the reservoir and power plant and prior to the commencement of dewatering operations. Recent changes are those changes that have been observed up to the present time and that are primarily the result of dewatering and the filling of Cookson Reservoir. Predicted long-term changes include not only the quantity and quality effects within the ground-water systems but also the estimated effects on quantity and quality of surface-water flows.

1. Baseline Conditions and Recent Changes
   (a) Field investigation of the areal extent, thickness and hydrogeologic properties of the Hart coal seam and overlying aquifers in northern Montana carried out during the course of the present GWQQC study indicated that the seam is not present everywhere in Montana and, furthermore, that it tends to be much less permeable there than in the areas where it is to be mined by the SPC.
   (b) Results of the GWQQC field sampling program established that earlier determinations of Poplar River Basin ground-water chemical quality characteristics were reasonably satisfactory in most cases and for most purposes. However, ground-water sampling, handling and analytical techniques for these earlier determinations were not standardized. Standardized techniques are nevertheless required for precise scientific work and for accurate measurement of critical parameters such as boron.
   (c) The chemical quality of the ground water in the formations below the glacial deposits and preglacial Empress Group sands and gravels often exceeds, under natural conditions, the criteria established by the Uses and Water Quality Objectives Committee of the IPRWQB. Considering only the nine ground-water samples collected by the GWQQC in the study area, the following chemical parameters exceeded the established criteria: iron, manganese, nitrate, nonionized ammonia, phenols, copper, fluoride, sodium absorption ratio, sulfate, zinc, and selenium.
   (d) Small uranium-roll deposits may be present above the Hart coal seam throughout the area. These deposits are generally characterized by relatively high concentrations of uranium and selenium. If these deposits are present, dewatering could give rise to increased concentrations of uranium and selenium in nearby ground waters and the mining operation could lead

to similar changes in the chemical quality of water percolating through spoil piles.

(e) Up to the present time, there have been no transboundary quantity or quality impacts to ground water as a result of the mine dewatering operations.

(f) Transboundary impacts to ground water as a result of the filling of Cookson Reservoir have so far been limited to a small rise in water levels in the shallow aquifers. This small rise indicates little transport of water from the reservoir to Montana through the ground-water system.

(g) A number of strip-mining, dewatering and/or power-plant operations appear to resemble the SPC plant at Coronach. These might be expected to provide some insight into expected hydrogeologic impacts at the SPC plant site. However, closer examination of data from the other sites indicates that none provides a close enough hydrogeologic analogue to warrant a detailed comparison. Among the cases considered but rejected were the Boundary Dam and associated power development at Estevan, Saskatchewan; and the Decker and Colstrip mines in Montana.

2. Predicted Long-Term Quantity Changes

(a) Maximum drawdown of water levels in the upper Fort Union aquifer of Montana (Canadian equivalent - upper Ravenscrag) is predicted as 0.7 m near the International Boundary after 35 years of mine dewatering.

(b) Maximum projected rise of water levels in the upper Fort Union aquifer of Montana is predicted as 0.1 m near the International Boundary after 75 years of reservoir leakage.

(c) Surface-water depletion caused by mine dewatering and the operation of Cookson Reservoir is predicted to be much more pronounced in Saskatchewan than in Montana. Maximum predicted streamflow depletion in Montana is 100 m^3/d for Goose Creek; predicted depletion for the Poplar River in Montana is only 25 m^3/d; predicted depletion for other streams in Montana is even less.

(d) Estimates presented in the final consultant's report suggest seepage through the sides and bottom of Cookson Reservoir and discharging into the East Poplar River downstream from Morrison Dam is not likely to exceed a few hundred cubic meters per day. These estimates assume that the subsurface flow paths between the reservoir and the river are principally through till or upper Ravenscrag Formation clays and sands.

(e) Assuming that no special measures are taken to isolate the ash lagoons from the ground-water system and that all subsurface leakage from the lagoons flows through the Empress Group and discharges into the East Poplar River downstream from Morrison Dam, the estimated maximum possible flow contribution to the

river from this source would be about 350 m^3/d. A part of the lagoon seepage, however, will almost certainly be diverted towards Cookson Reservoir and the actual direct lagoon seepage contribution to East Poplar River will probably be appreciably less than 350 m^3/d.

3. Predicted Long-Term Quality Changes
   (a) The projected increase in the temperature in Cookson Reservoir because of SPC plant operations will have negligible effects of ground-water quality.
   (b) The quality of ground water moving across the International Border will not be degraded as a result of the SPC power plant operation.
   (c) Degradation in ground-water quality as a result of leakage from Cookson Reservoir will be limited primarily to the aquifers above the Ravenscrag Formation. Any such degradation is expected to be minor except in the case of conservative constituents such as nitrate and boron.
   (d) There may be an increase in the size and number of saline-affected areas in Montana because of a rise in the water table related to the storage of water in Cookson Reservoir.
   (e) The ash lagoons as currently proposed present a high potential for contamination of ground water and for discharge of contaminated ground water into surface water. The danger of surface-water contamination is a function of the rate of discharge of ash lagoon leakage to the East Poplar River as discussed in conclusion 2(e) above and is subject to the same assumptions. In addition, it should be noted that the uncertainty associated with metal and trace element mobility in ground water requires, for estimation of chemical-quality impacts from the ash lagoons, that these potential contaminants be considered to remain in solution and move unattenuated with the ground water. Practical experience might show some of these contaminants are retarded due to sorption, precipitation or other phenomena.
   (f) Leakage to the ground water from any of the ancillary facilities such as coal piles, evaporation pond for coal pile runoff, sewage lagoons, spray irrigation of sod farms, maintenance operations, and the cooling water channel, could also cause severe ground- and surface-water contamination.
   (g) The chemical quality of the ground water discharging to the East Poplar River below Morrison Dam (other than that originating in the ash lagoons) could eventually approach the chemical quality of Cookson Reservoir. This is most likely to be the case with conservative constituents such as boron. The result would be to degrade the water quality of the East Poplar River crossing the International Border.
   (h) After recovery from pumping, the drainage of ground water from the spoil areas adjacent to Girard Creek could cause deterioration of water quality in Girard Creek during low-flow

periods. In addition, dewatering wells draining spoil areas could discharge degraded water to Girard Creek. Degradation would consist primarily of an increase in dissolved solids. The degraded water would be mixed with, and diluted by other water in Girard Creek and in Cookson Reservoir.

(i) The chemical quality of water in bank storage in alluvial deposits adjacent to the East Poplar River downstream from Morrison Dam will probably become similar to the average quality of water released form Cookson Reservoir. This effect should become less important as distance from the river increases because of the flushing effect of ground water moving towards and discharging into the stream.

Recommendations

The recommendations advanced as a result of the GWQQC study fall into a number of distinct categories. Firstly, there are those dealing with the prevention or minimization of ground-water contamination. In these cases the possible contamination levels for ground water and, eventually perhaps, for surface water are believed to be high enough to justify special measures to eliminate or significantly reduce infiltration of the contaminated waters into the subsurface. Secondly, there are a number of recommendations for the future monitoring of ground-water levels and pumping rates and thirdly a parallel set of recommendations for ground-water quality monitoring. The monitoring recommendations, if implemented, should provide adequate early warning of significant water-level or chemical-quality changes arising out of SPC activities; they also have potential value in checking the predictive capabilities of the two mathematical models described in earlier sections and for designing improvements in the models, should that be necessary.

A fourth category of recommendation is concerned with some of the input parameters utilized in the mathematical ground-water models and with the possibility for major deviations from some of the basic assumptions on which development of the models was based. Major deviations of this kind could invalidate some or all of the model predictions. Future monitoring of environmental effects should thus be carried out in full awareness of the significance of such major deviations.

A last but very important recommendation suggests the need for the creation of a board or other body for the periodic monitoring and review of ground-water changes occurring as a result of SPC power generation activities at the Coronach plant. Other IPRWQB committees may also see the need for such a board with, however, a much broader range of responsibilities covering all aspects that have been under study by the IPRWQB.

1. Contamination Prevention
   - (a) While drilling for exploration or production, SPC should check the core and/or cuttings with a scintillometer for radioactivity. If anomalously high readings are observed, care should be taken in the excavation and re-emplacement of this material, since it may contain abnormally large amounts of uranium and selenium. Care in handling could minimize the potential for mobilization of these two elements.
   - (b) The ash lagoons should be lined with a relatively impermeable clay/sand mixture, with plastic or some other impermeable material in order to prevent infiltration of ash lagoon leachate into the ground-water system.
   - (c) Ancillary facilities such as coal piles, sewage lagoon, maintenance facilities and hydrocarbon storage tank areas should

be located wherever possible on low-permeability, fine-grained material in order to prevent leakage to the ground-water system. If proposed sites are not suitable from this point of view, lining as in recommendation 1(b) above may be necessary.

2. Monitoring of Ground-Water Levels and Pumping Rates
   (a) Water levels in observation wells in Montana should be measured and recorded on a periodic basis. Observations wells GWQQC 1-10 listed in Table 2 and well 37N 48E5AAAA will provide an adequate group of wells for purposes of measuring water levels. The measurement of water levels should be every three months from a standardized reference datum. Water-level measurements should continue during the active dewatering and mining period and during the recovery period until water levels recover to reasonable levels.
   (b) A network of wells to measure changes in water levels near Cookson Reservoir also should be selected. This well network should be used to determine the effect of the reservoir on water-table elevation and potential saline-affected areas. Observation wells outside the area of influence of the reservoir also should be established to compare natural water-level changes with those resulting from reservoir leakage.
   (c) The discharge rate for each dewatering well should be regularly measured and recorded, either by reading directly from a rate meter or by calculation from a cumulative volume meter. Regardless, the rate for each well should be measured weekly and discharge rates should be compared with estimated rates listed in Table 10.
   (d) The water-level monitoring network should be reviewed periodically to assess its adequacy. Wells and piezometers should be capped and locked to prevent vandalism. They should be maintained in good working order and replaced if damaged beyond repair. If new wells or piezometers are added to the network, all pertinent well construction and completion data should be recorded.

3. Monitoring of Ground-Water Quality
   (a) A comprehensive, accurate and reliable set of baseline ground-water chemistry data should be collected before power generation begins at the SPC Coronach plant. This data set should include at least three complete samplings from the Saskatchewan Research Council's regional piezometer network and from other appropriate available sampling points, such as the Montana water-level observation network (see recommendation 2(a) above). The first such sampling was carried out in 1976. The GWQQC has already urgently recommended to the IPRWQB (in a memorandum dated 11 September 1978) that a second sampling be done before the end of October 1978. A third (and possibly a fourth) sampling can be done in 1979 before start-up of the plant.

(b) Sampling procedures utilized in the collection of the baseline chemical-quality samples should be those recommended by the GWQQC; the parameters to be analyzed should also conform to GWQQC recommendations although other parameters could be added at the suggestion of other committees of the IPRWQB.

(c) Subsequent to the commencement of power generation, ground-water quality should be monitored regularly in selected wells and piezometers in order to detect any movement of contaminated ground waters southward from the SPC properties towards the International Boundary.

(d) The aquifers above the Ravenscrag Formation near Cookson Reservoir should be monitored separately for ground-water quality degradation for the period of the SPC power plant operations. Control water-quality monitoring wells also should be established outside the area affected by Cookson Reservoir.

(e) Exploratory test drilling should be conducted in the area between the proposed ash lagoon site and the East Poplar River between Morrison Dam and the International Boundary. If the Empress Group sands and gravels are encountered, observation wells for water-quality monitoring should be installed at selected sites in order to monitor movement of contaminated ash lagoon waters through the subsurface toward the East Poplar River.

(f) The recommendation (see 2(d) above) concerning review, maintenance, and repair of the water-level network applies equally to the chemical-quality network. In addition, complete information on the water sampling point within the distribution system and on the location of water softeners, iron removers, etc. in the systems also should be recorded.

(g) The first spoil areas should be surveyed to determine changes in ground-water chemical quality within and adjacent to the spoil pile zones. Should degraded ground-water quality be evident, mining and reclamation procedures should be evaluated and modified if necessary.

4. Input Parameters and Assumptions

(a) Model predictions of the quantity and quality behavior of the ground-water system depend on the availability of good estimates of leakage from Cookson Reservoir. In order to provide these estimates, continuous measurements are needed for the surface-water inflow to the reservoir, precipitation on the reservoir, evaporation from the reservoir, reservoir storage volume, and seepage around and through the dam. These measurements should be used in the preparation of water budgets, from which leakage would be determined as a residual.

(b) One of the boundary conditions for the finite-difference ground-water model was that Girard Creek constituted a line of constant hydraulic head. In essence, this means that the model assumes

that flow in Girard Creek is maintained at all times. If this flow is interrupted or if valley-fill alluvium in the creek becomes dewatered, the model predictions could be invalidated. In any future evaluations or reviews of environmental effects, the reviewing body should bear in mind the implications of zero flow in Girard Creek on model predictions and should arrange for a re-analysis using a more appropriate model, if this should seem to be warranted.

(c) Other major deviations from assumed conditions that could invalidate or seriously modify ground-water model predictions include: (i) major reductions or increases (say, 50 percent or more) in the assumed pumping rates for the dewatering wells; (ii) excessive reduction of the water level in Cookson Reservoir below full supply level, or (iii) a major reduction in leakage from the reservoir into the ground-water system as a result of deposition in the reservoir of fine-grained low-permeability materials. As before, a review body should be aware of the implications of these changes as far as the original ground-water model prediction are concerned.

5. Review Board

(a) An impartial review board should be created for the periodic evaluation of the significance of ground-water quantity and quality changes revealed by the monitoring networks and of other evidence collected through the years. The board should be empowered to make recommendations concerning changes in ground-water monitoring procedures and schedules, as well as in plant operating procedures in those cases where they have reason to believe existing or potential ground-water contamination problems could be alleviated thereby. The board also should be aware of the limitations on ground-water model predictions imposed by the original model assumptions and should be prepared and empowered to arrange for reanalysis by a more appropriate model should this appear to be warranted on the basis of their periodic reviews. Preferably such a board should also have responsibility to evaluate other changes of interest (surface water, biological, and so forth) and the power to act on all their findings in a similar fashion. The GWQQC suggests that such review should be carried out at least every five years but a more frequent basis could be more satisfactory.

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Plates 1 — 10

Plate 1 Geologic map, upper Poplar River Basin, Saskatchewan and Montana

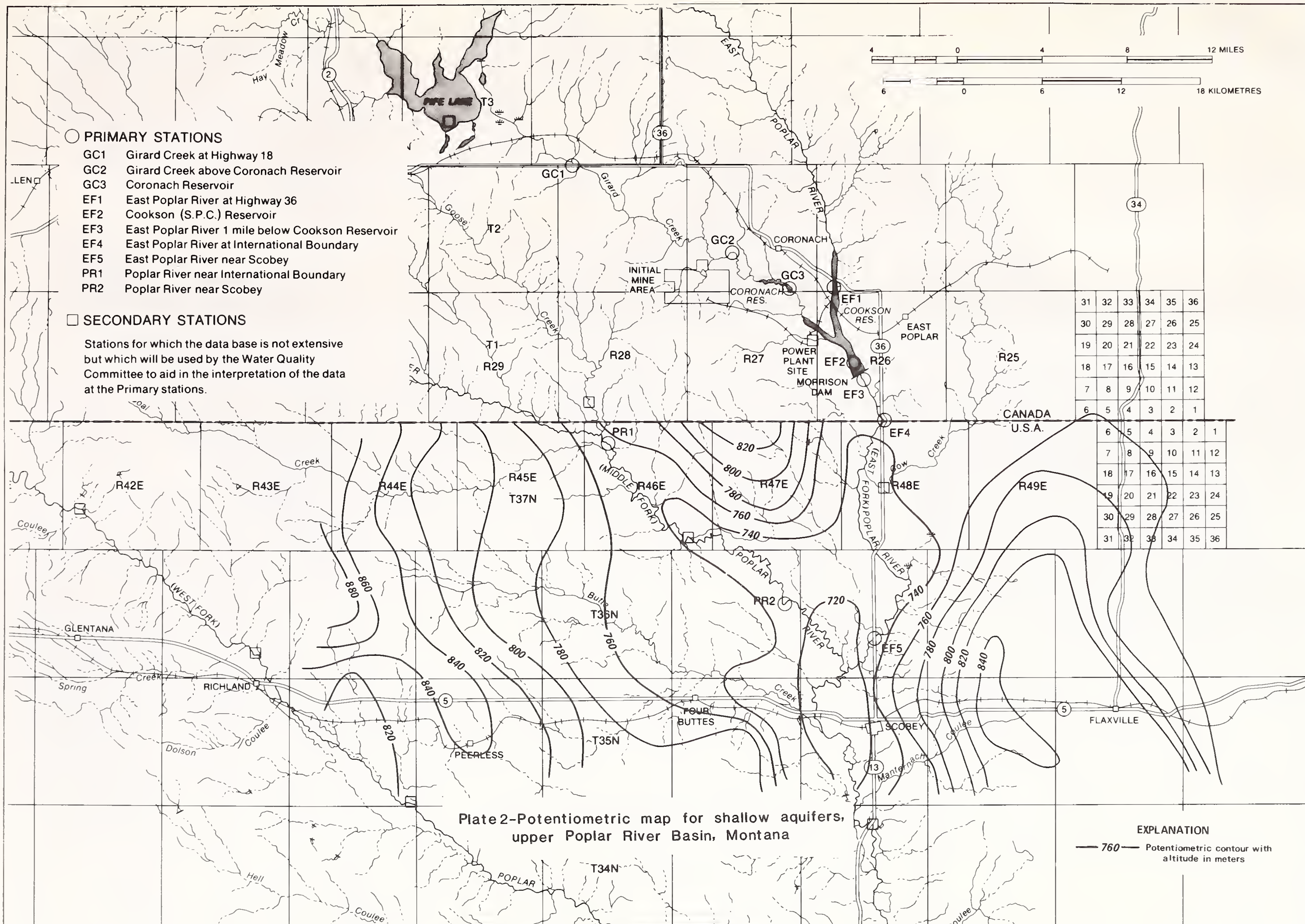


Plate 2-Potentiometric map for shallow aquifers, upper Poplar River Basin, Montana

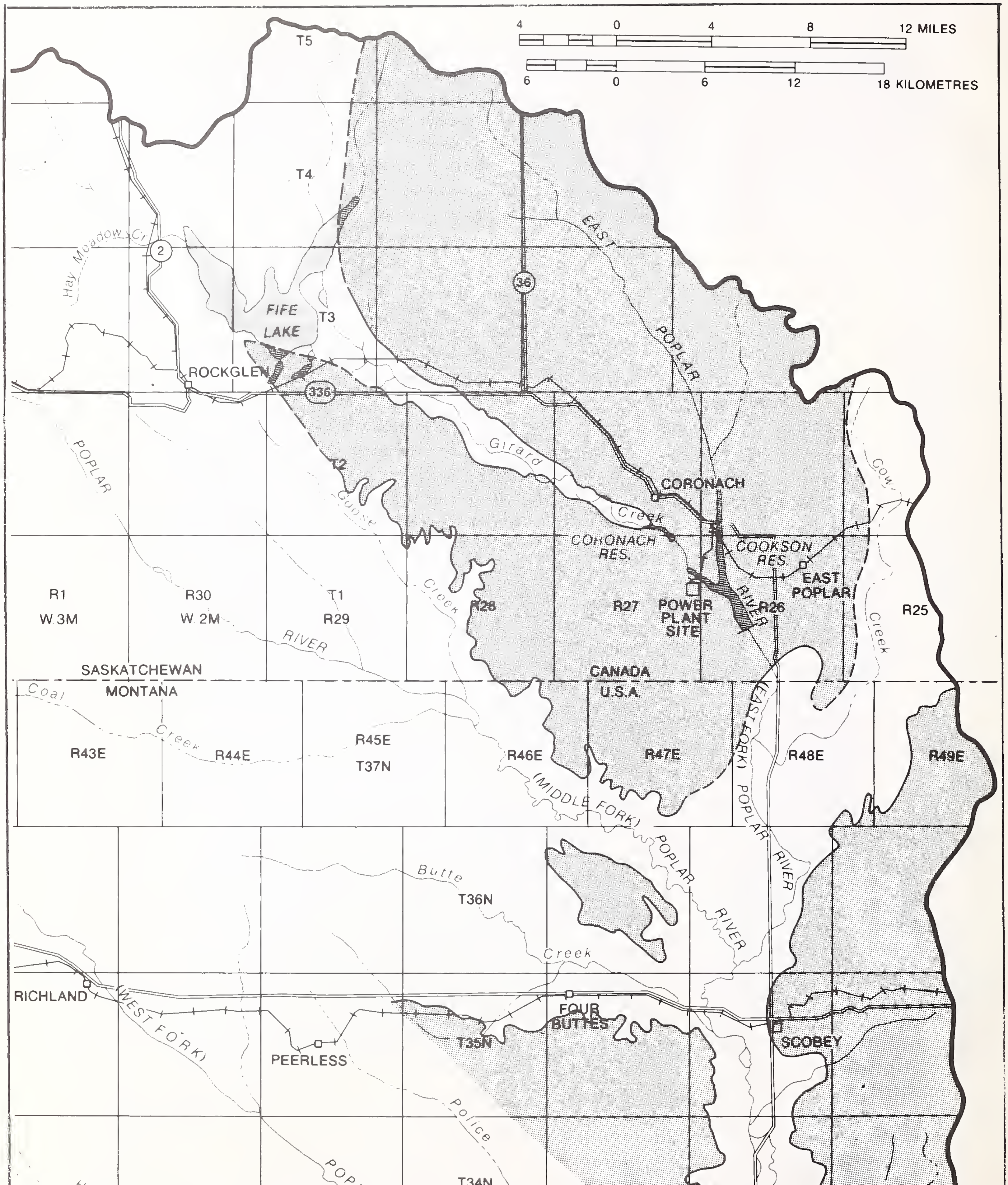
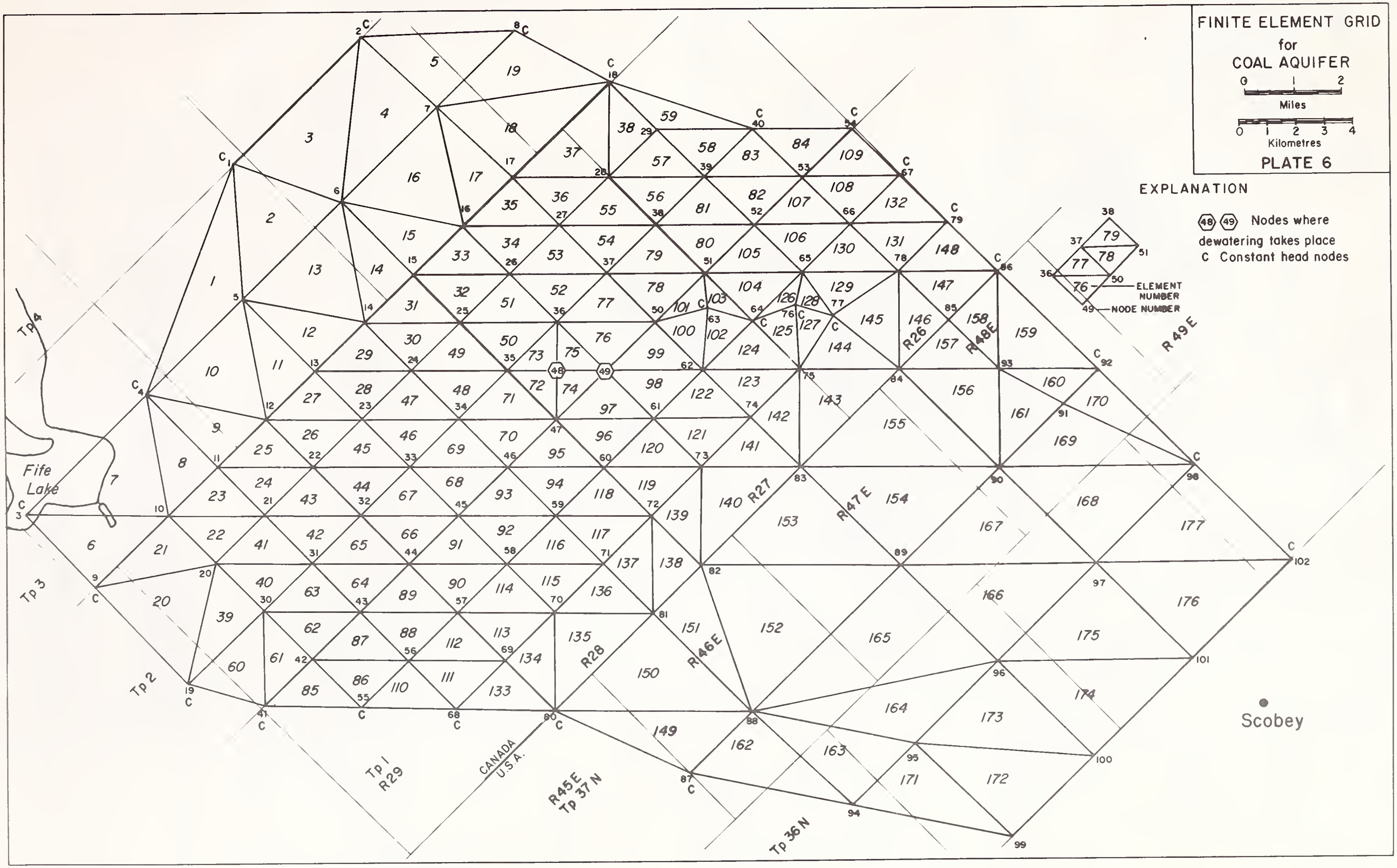


Plate 3 - Areal distribution of Hart coal seam in Saskatchewan and coal horizon D in Montana for part of upper Poplar River Basin.

Plate 4—Potentiometric map for Hart coal aquifer, upper Poplar River Basin, Saskatchewan

Plate 5–Potentiometric map for Frenchman aquifer, Saskatchewan and Fox Hills – basal Hell Creek aquifer Montana, upper Poplar River Basin


FINITE ELEMENT GRID
for
COAL AQUIFER
0 1 2
Miles
0 1 2 3 4
Kilometres
PLATE 6
EXPLANATION
48 49 Nodes where dewatering takes place
C Constant head nodes
ELEMENT NUMBER
NODE NUMBER
Fife Lake
Scobey
CANADA
U.S.A.
Tp 4
Tp 3
Tp 2
Tp 1
R29
R28
R27
R26
R45E
R46E
R47E
R48E
R49E
Tp 37 N
Tp 36 N

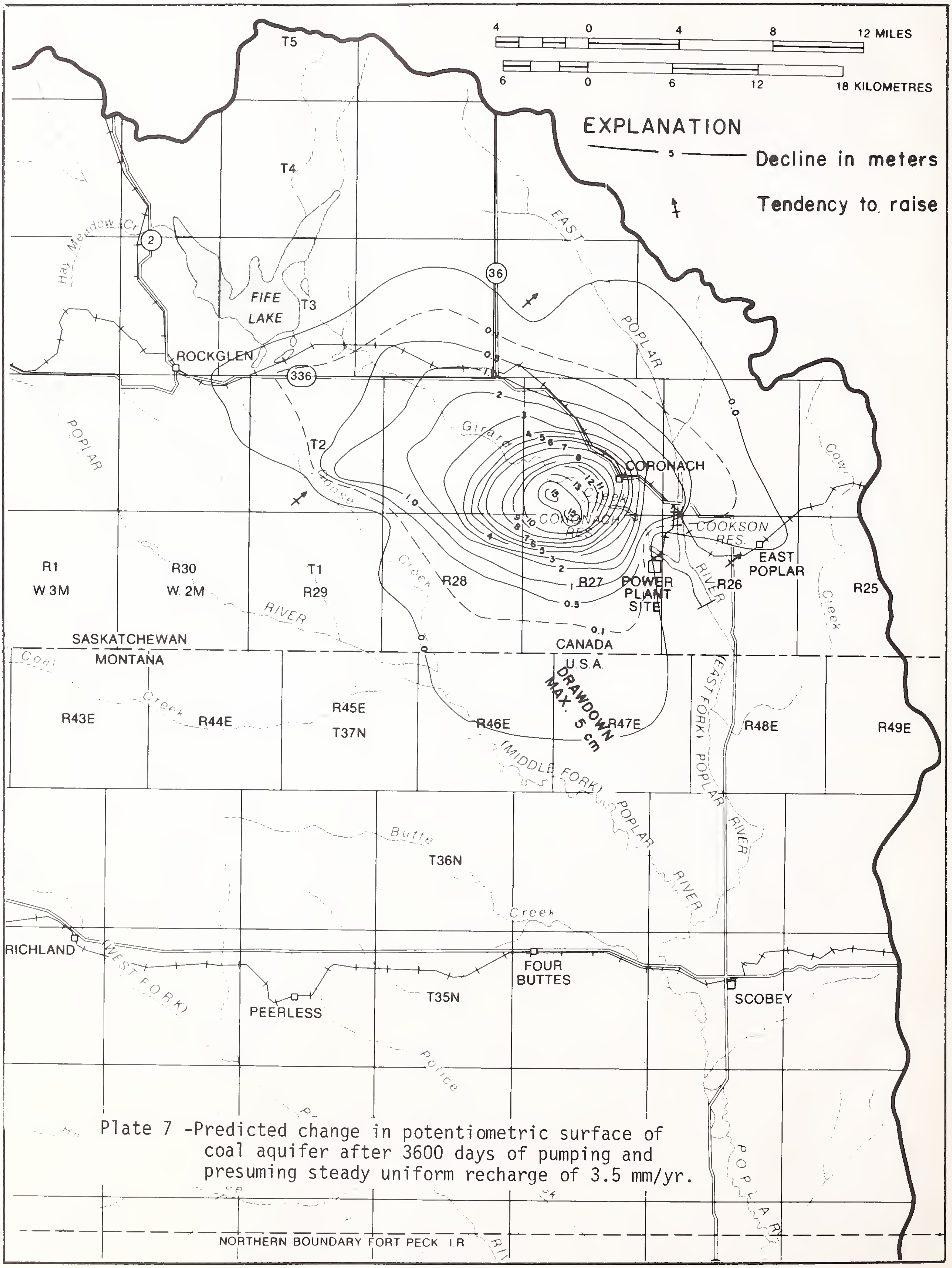


Plate 7 -Predicted change in potentiometric surface of coal aquifer after 3600 days of pumping and presuming steady uniform recharge of 3.5 mm/yr.

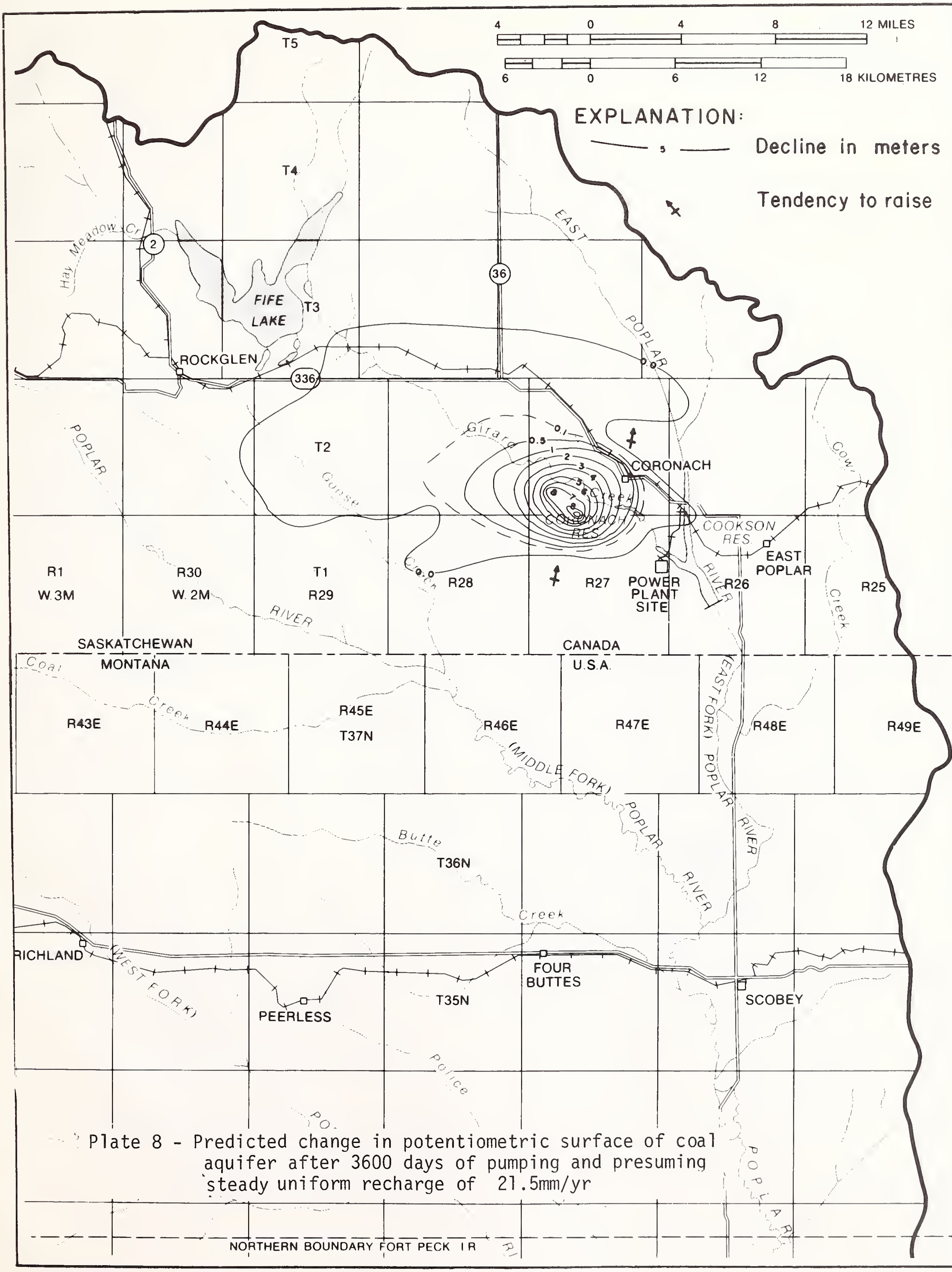


Plate 8 - Predicted change in potentiometric surface of coal aquifer after 3600 days of pumping and presuming steady uniform recharge of 21.5mm/yr

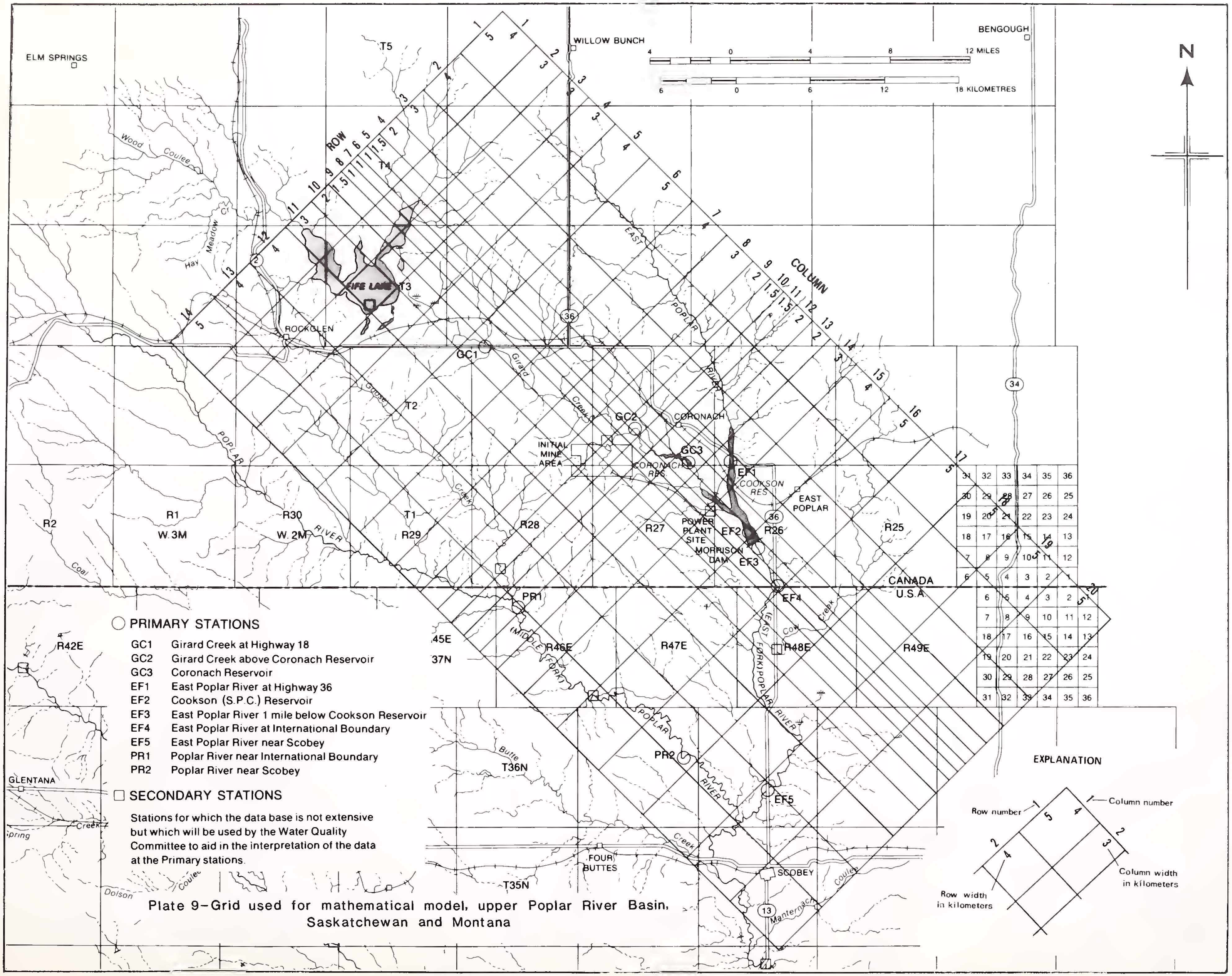


Plate 9–Grid used for mathematical model, upper Poplar River Basin, Saskatchewan and Montana

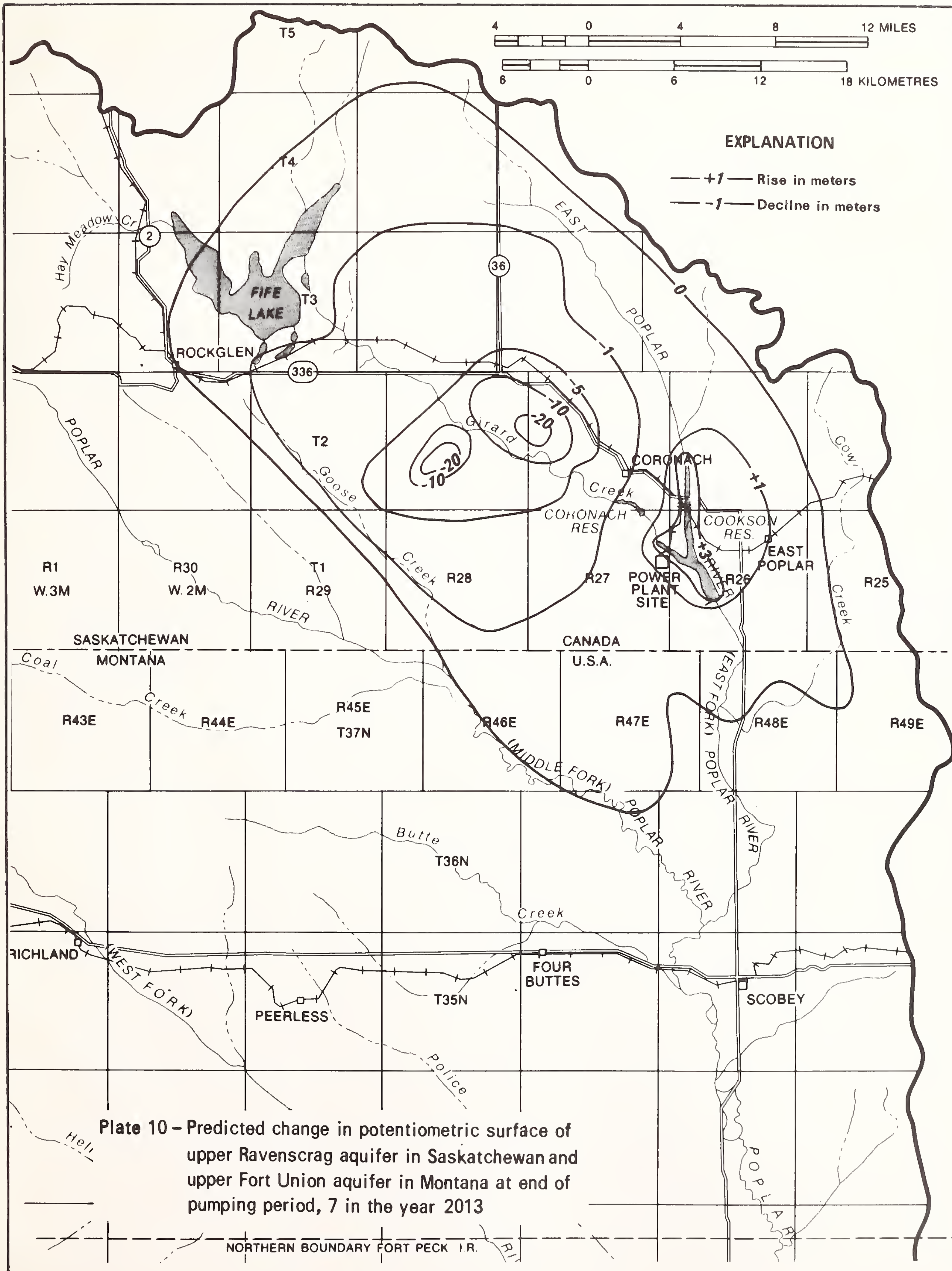


Plate 10 – Predicted change in potentiometric surface of upper Ravenscrag aquifer in Saskatchewan and upper Fort Union aquifer in Montana at end of pumping period, 7 in the year 2013